

PHENIX results on charged-hadron azimuthal anisotropies in Au+Au collisions at center-of-mass energies from 39 to 200 GeV

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Contents

- Energy dependence of v_n in Au+Au
- Forward/Backward v_n in Cu+Au
- v_2 at high p_T at 200 GeV in Au+Au

Azimuthal anisotropic observables

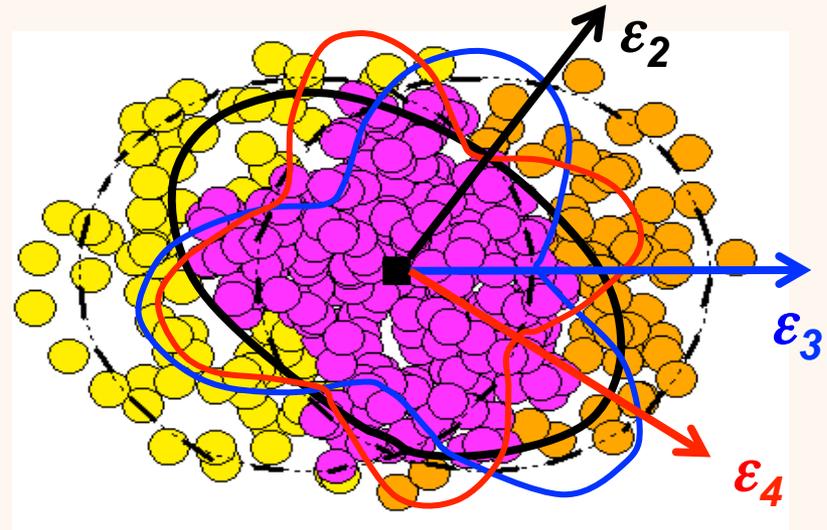
Anisotropic particle production is characterized by Fourier Coefficient v_n .

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1} 2 v_n \cos(n(\phi - \Psi_n))$$
$$v_n = \langle \cos[n(\phi - \Psi_n)] \rangle, n = 1, 2, 3, \dots$$

Initial geometrical anisotropy: ϵ_n



momentum anisotropy: v_n



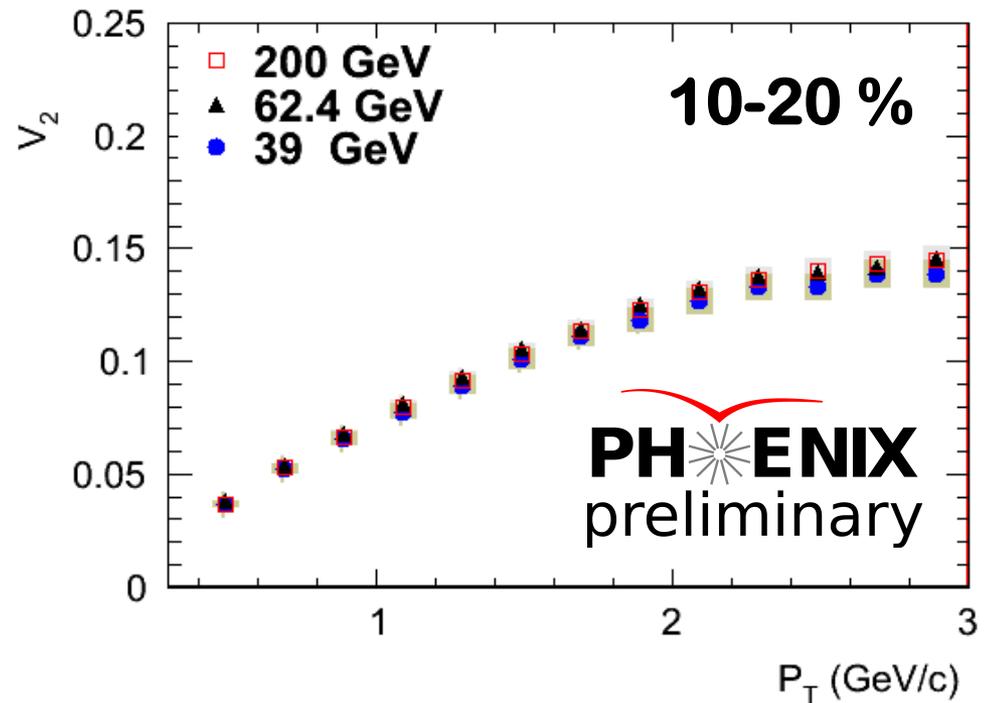
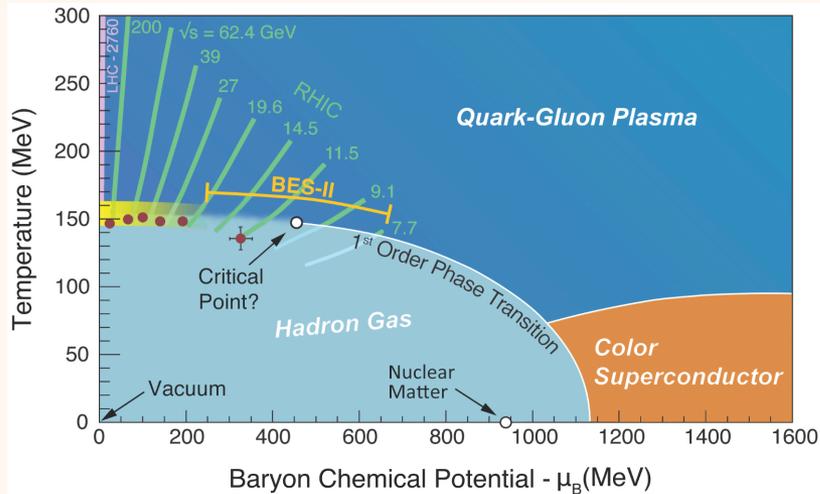
- v_n is sensitive to
- Initial condition
 - QGP properties (η/s , partonic level flow)

Energy dependence of v_n

v_2 at energy scan

Aim : to map out the QCD phase diagram.

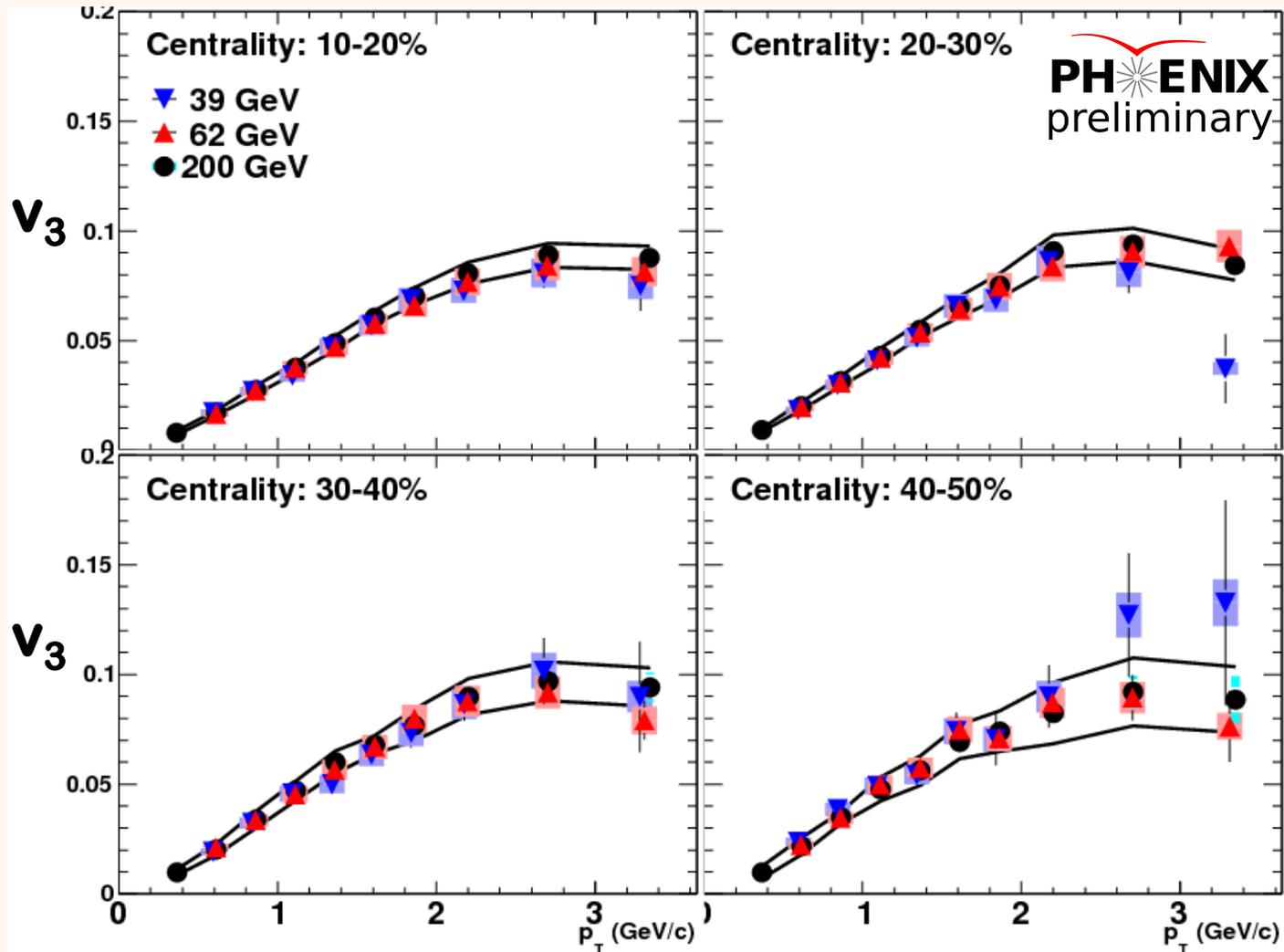
Illustration: Swagato Mukherjee



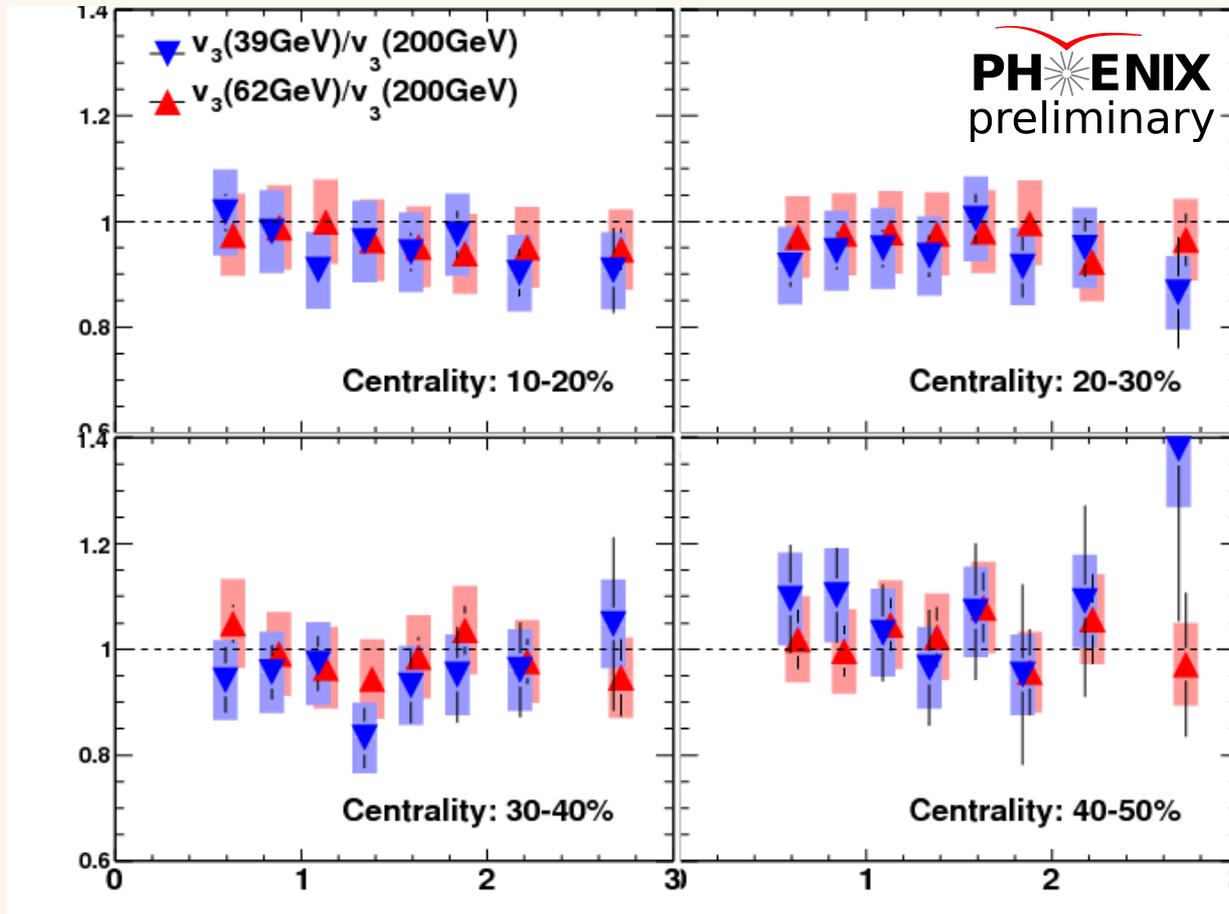
v_2 is not changing from 39 -200 GeV within uncertainty.

How about higher order harmonic v_3 ?

v_3 at 200, 62.4 and 39 GeV



Ratio of $v_3(39,62 \text{ GeV})/v_3(200 \text{ GeV})$

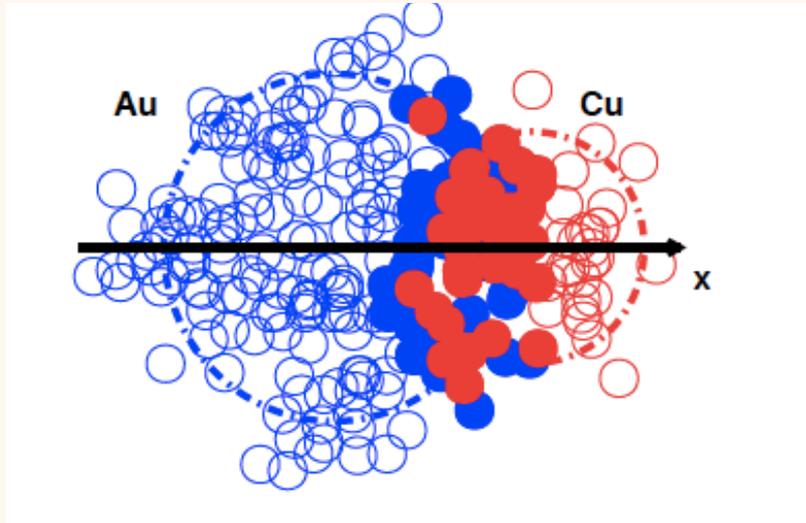


v_3 is also saturated for 39 – 200 GeV.

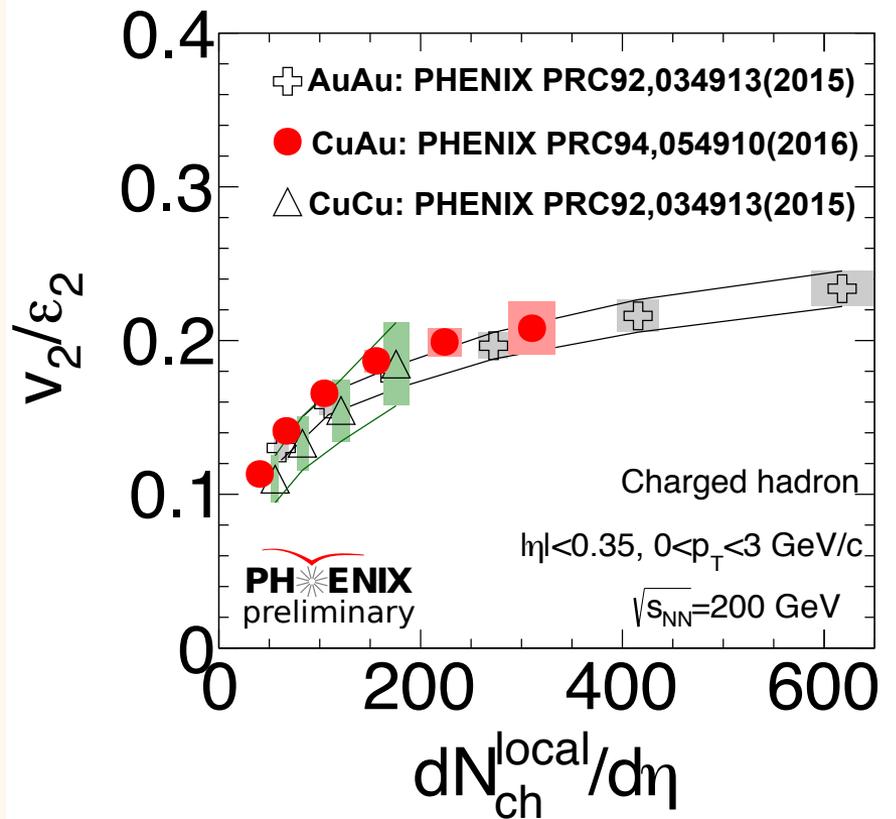
Forward/Backward v_n in Cu+Au

Details are described in Hiroshi Nakagomi's Poster[***K03***]

v_n in Cu+Au (mid-rapidity)



Cu+Au collisions provide additional insight of initial geometry(ϵ_n) effect.



- v_2 /eccentricity($dN/d\eta$) does not depend on the collision systems at mid-rapidity.

How about forward and backward ?

Possibilities

1. Asymmetric initial geometry due to initial-state fluctuations along η : $\epsilon_n(\eta) \neq \epsilon_n(-\eta)$
2. Twisted plane azimuth: $\Psi_n(\eta) \neq \Psi_n(-\eta)$
3. Asymmetric energy density: $dN/dn(\eta) \neq dN/dn(-\eta)$

Asymmetric initial geometry



?



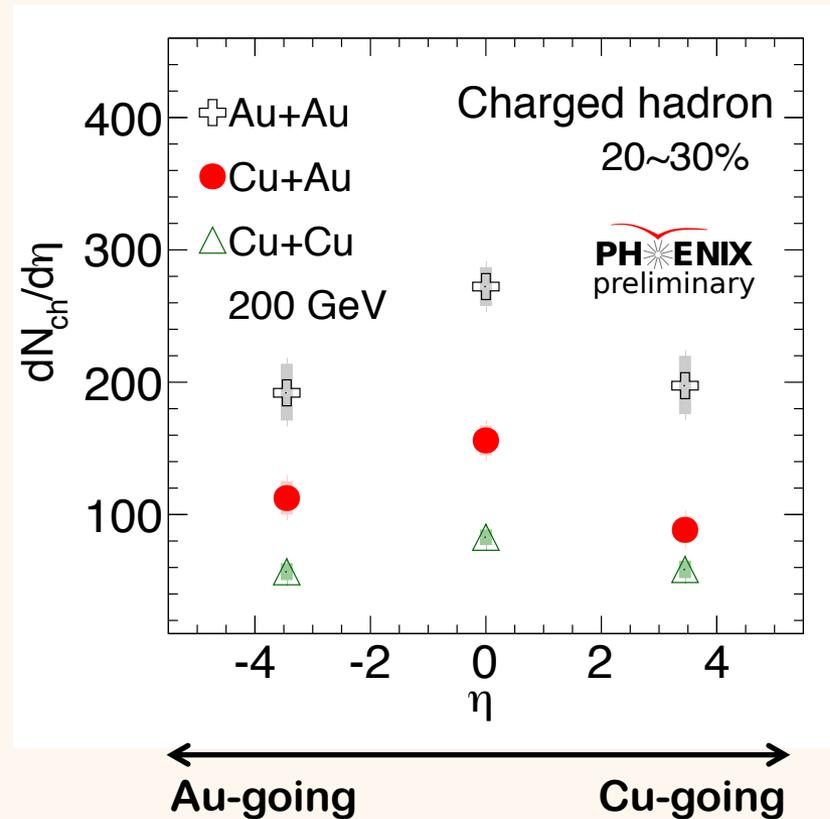
Boost invariance initial geometry



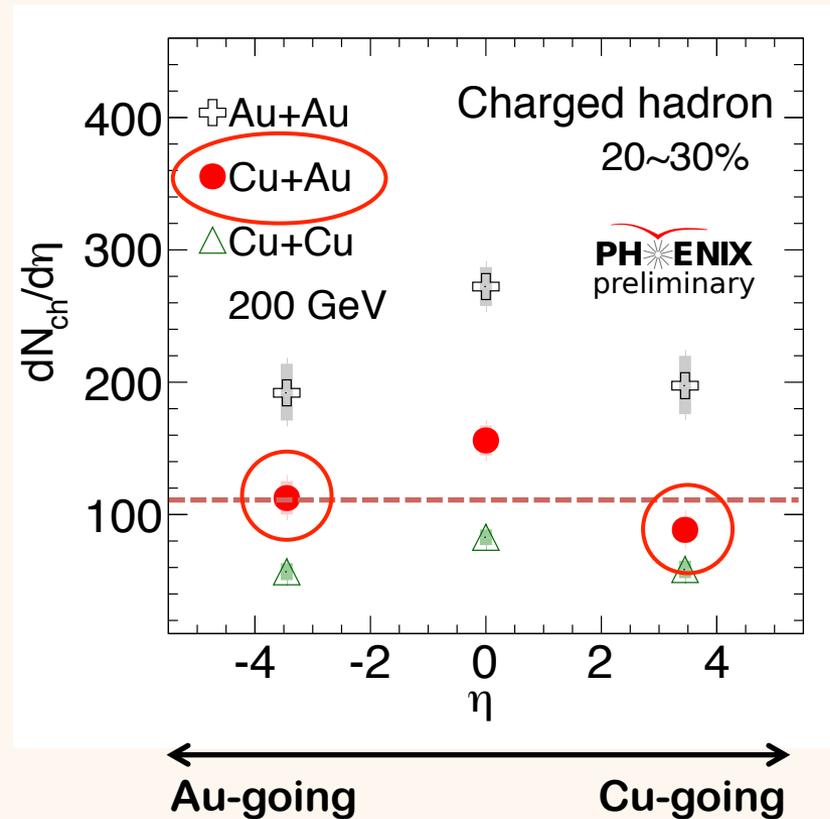
v_n in Cu+Au provides insight of longitudinal eccentricity effect.

→ Measure $dN/d\eta$ and v_n at forward/backward.

Charged particle $dN/d\eta$ (η) and $v_n(\eta)$



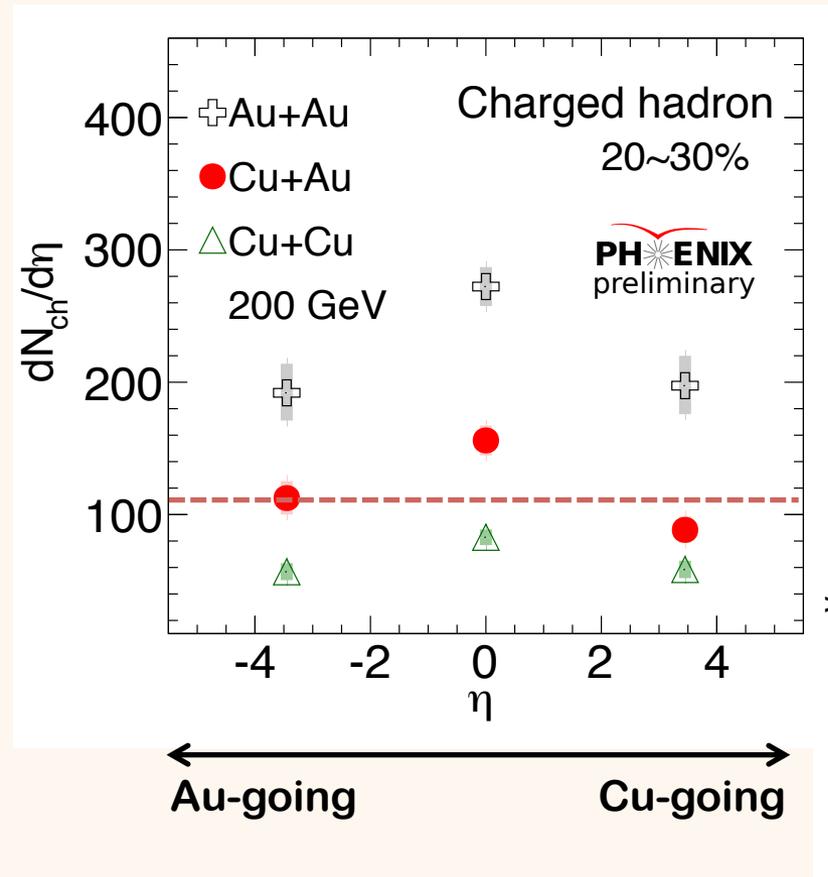
Charged particle $dN/d\eta$ (η) and $v_n(\eta)$



In Cu+Au

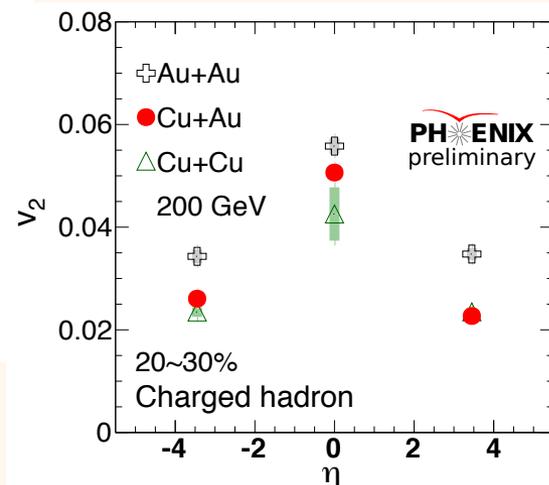
- $dN/d\eta(\text{Au-going}) > dN/d\eta(\text{Cu-going})$

Charged particle $dN/d\eta$ (η) and $v_n(\eta)$

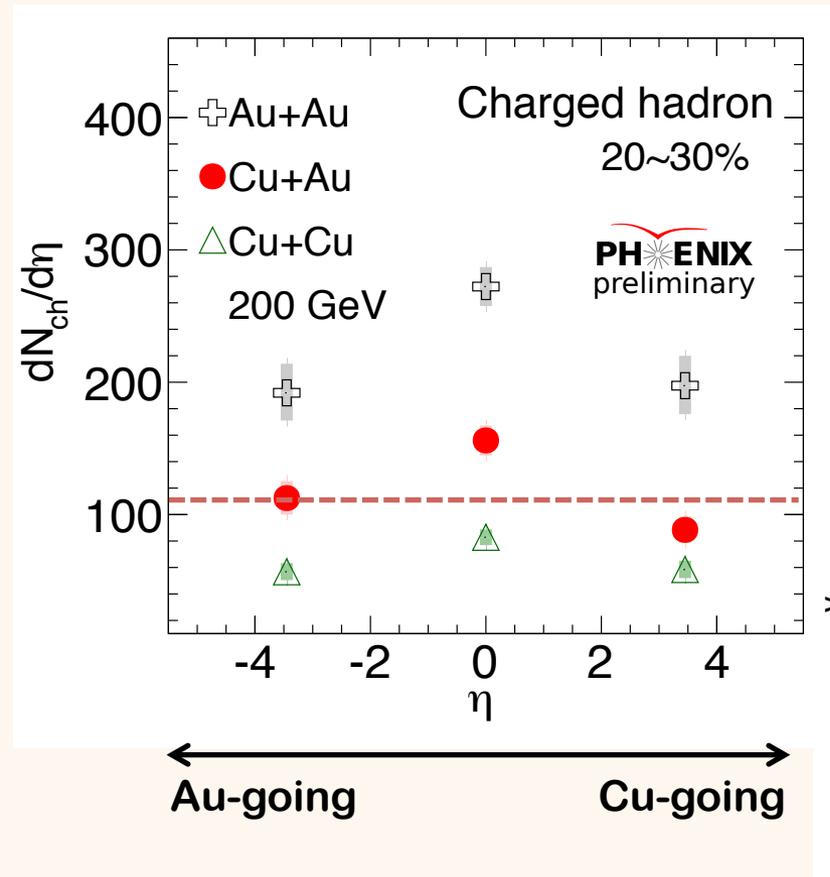


In Cu+Au

- $dN/d\eta(\text{Au-going}) > dN/d\eta(\text{Cu-going})$

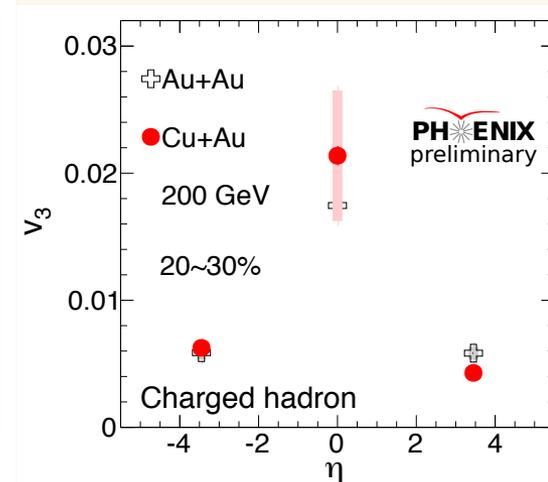
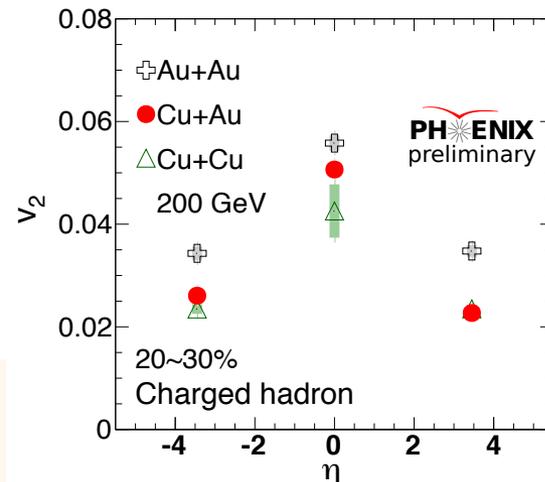


Charged particle $dN/d\eta$ (η) and $v_n(\eta)$

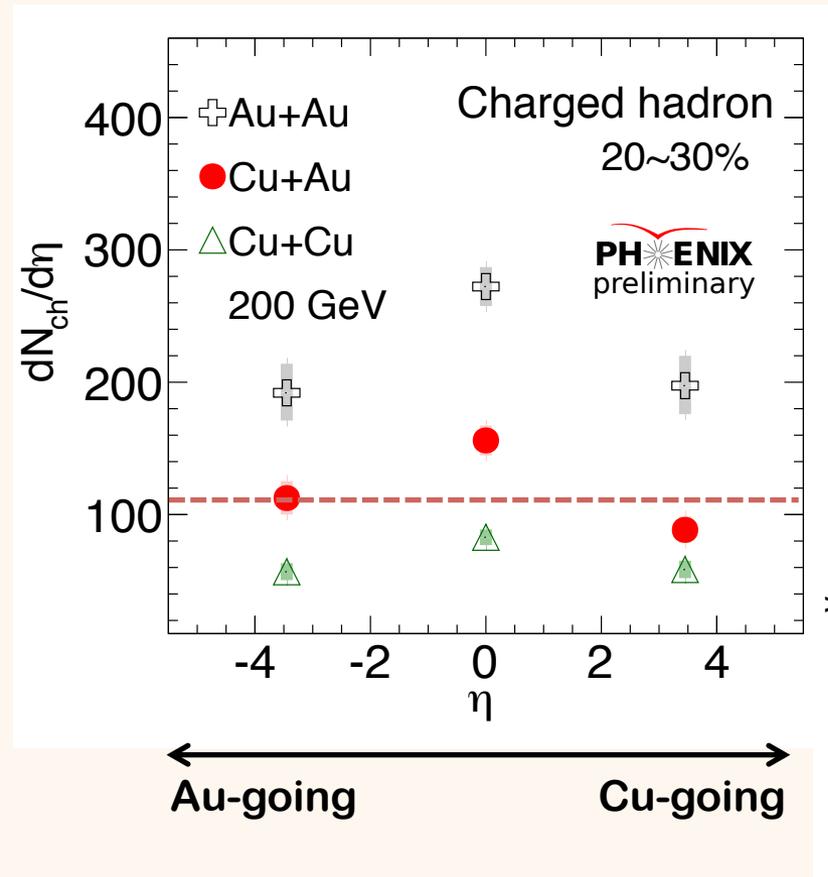


In Cu+Au

- $dN/d\eta(\text{Au-going}) > dN/d\eta(\text{Cu-going})$
- $v_n(\text{Au-going}) > v_n(\text{Cu-going})$

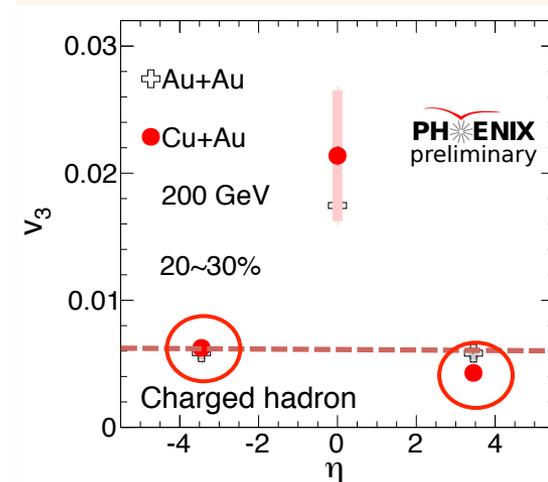
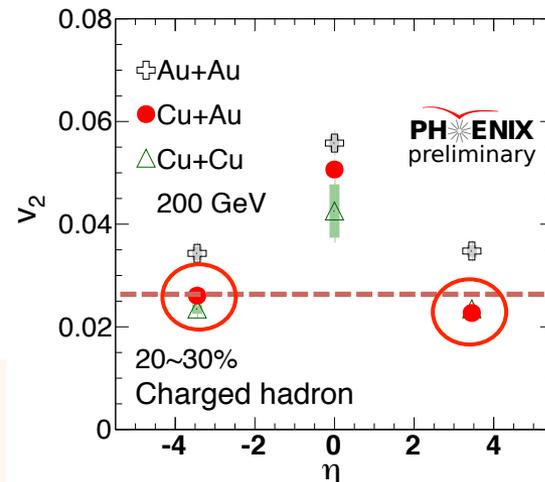


Charged particle $dN/d\eta$ (η) and $v_n(\eta)$



In Cu+Au

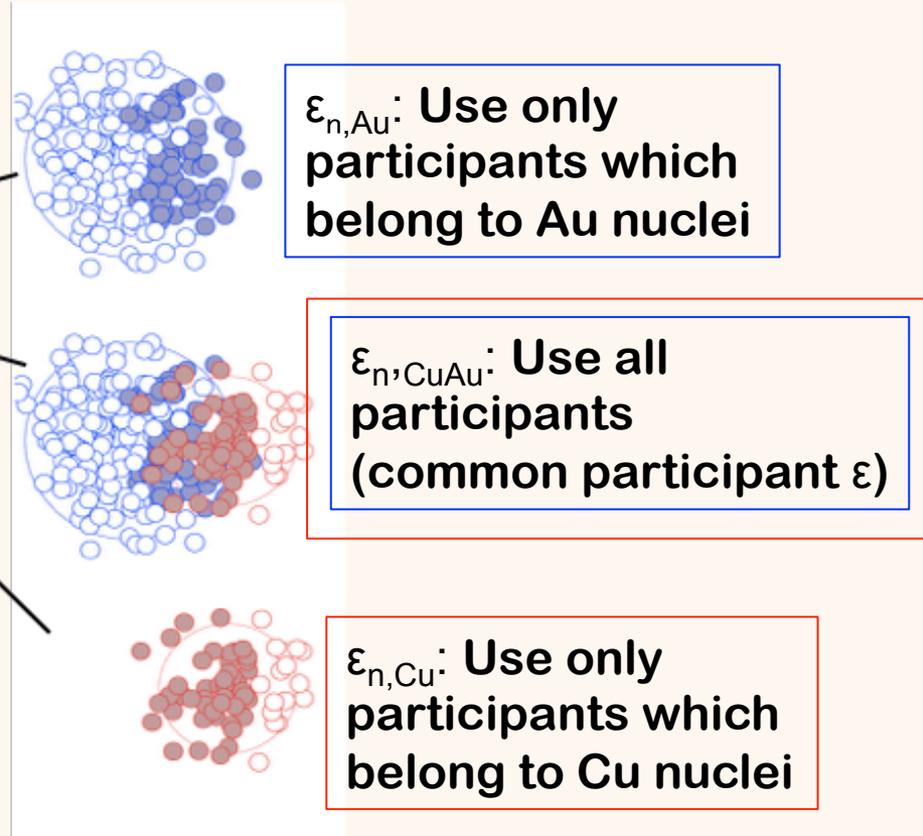
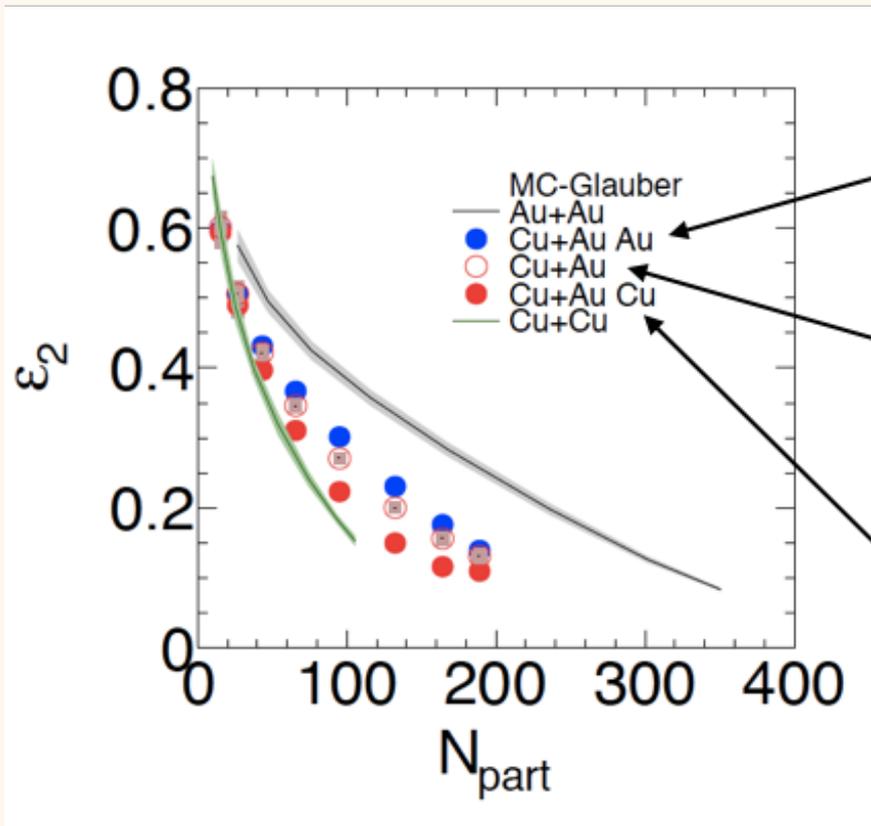
- $dN/d\eta(\text{Au-going}) > dN/d\eta(\text{Cu-going})$
- $v_n(\text{Au-going}) > v_n(\text{Cu-going})$



Possible definitions of eccentricity

$$\varepsilon_{n,Au(Cu)} = \frac{\langle r^n \cos[n(\phi_{Au(Cu)} - \Phi_{n,Cu+Au})] \rangle}{\langle r^n \rangle}$$

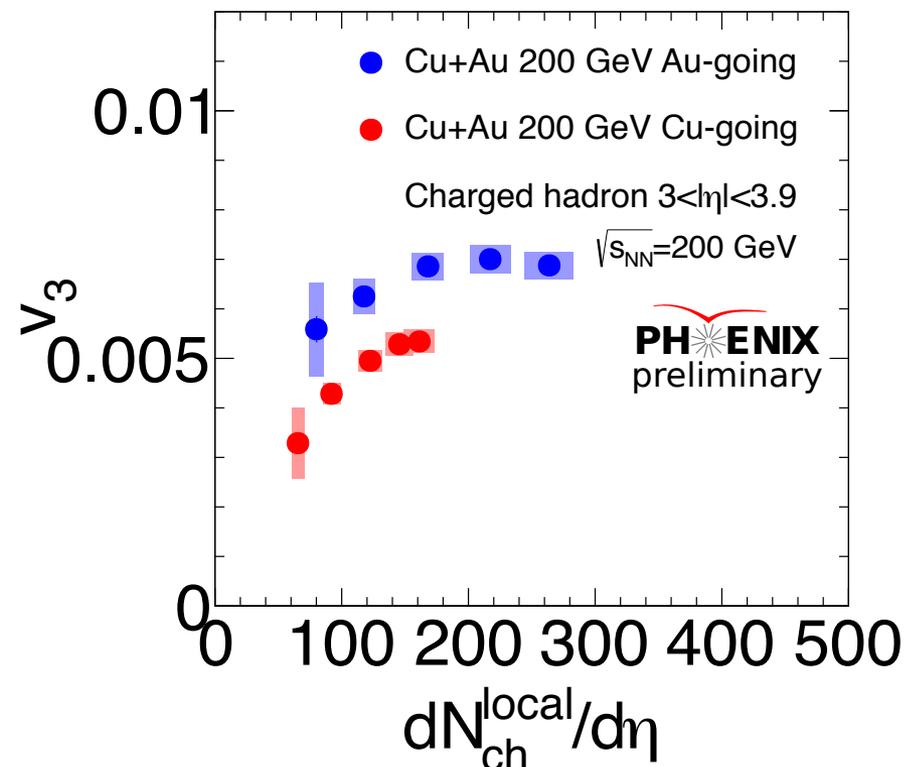
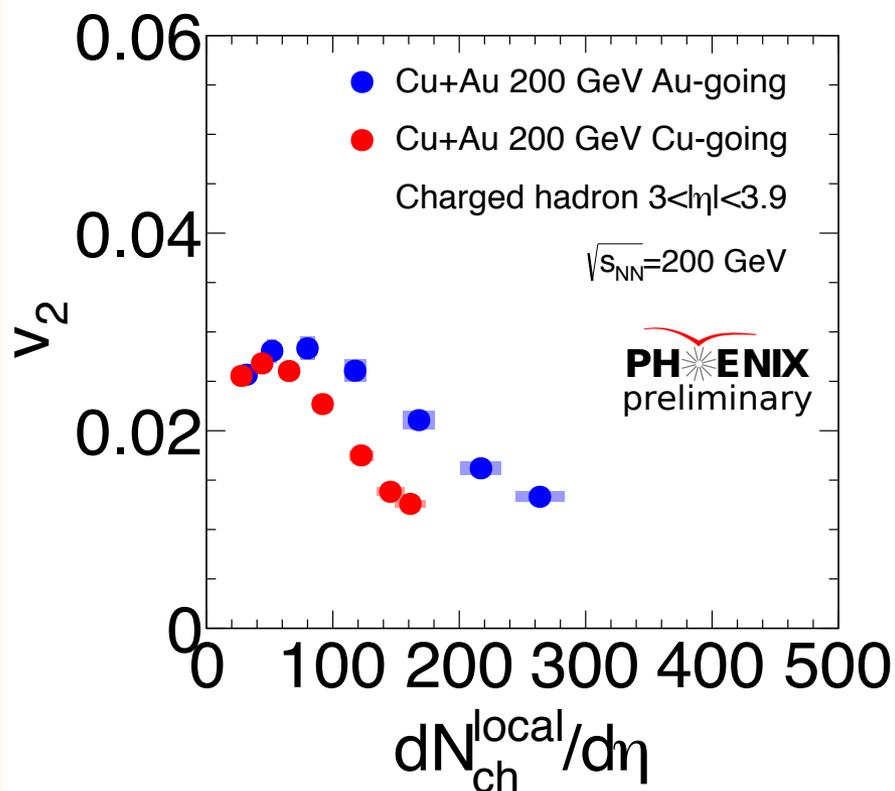
ε calculated by participant geometry with MC-Glauber model



Three types of ε are examined for eccentricity scaling.

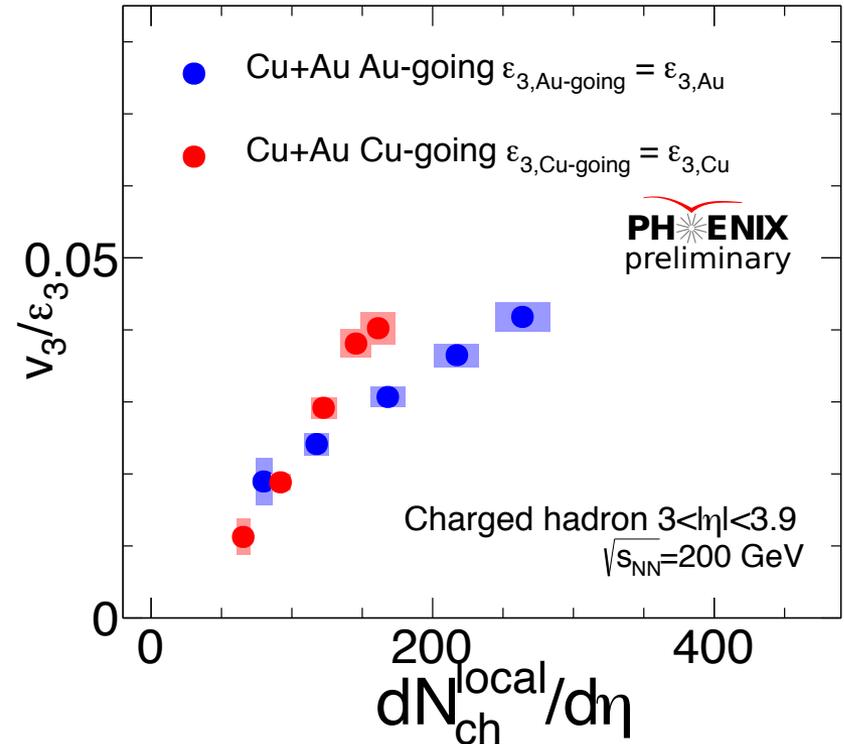
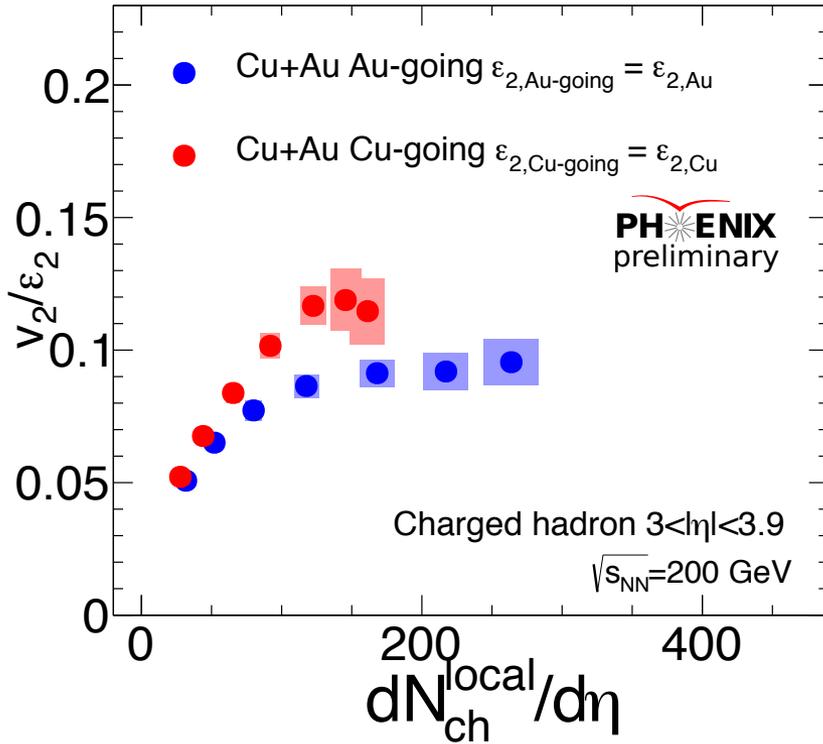
Forward/backward v_n vs. $dN_{ch}/d\eta$

$v_{n,Au-going}$ $v_{n,Cu-going}$



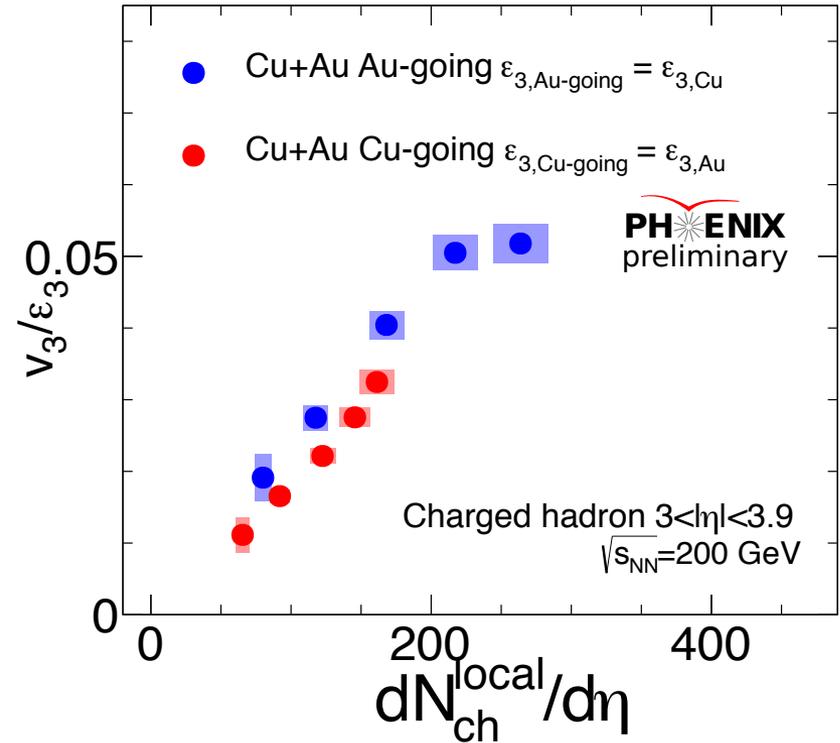
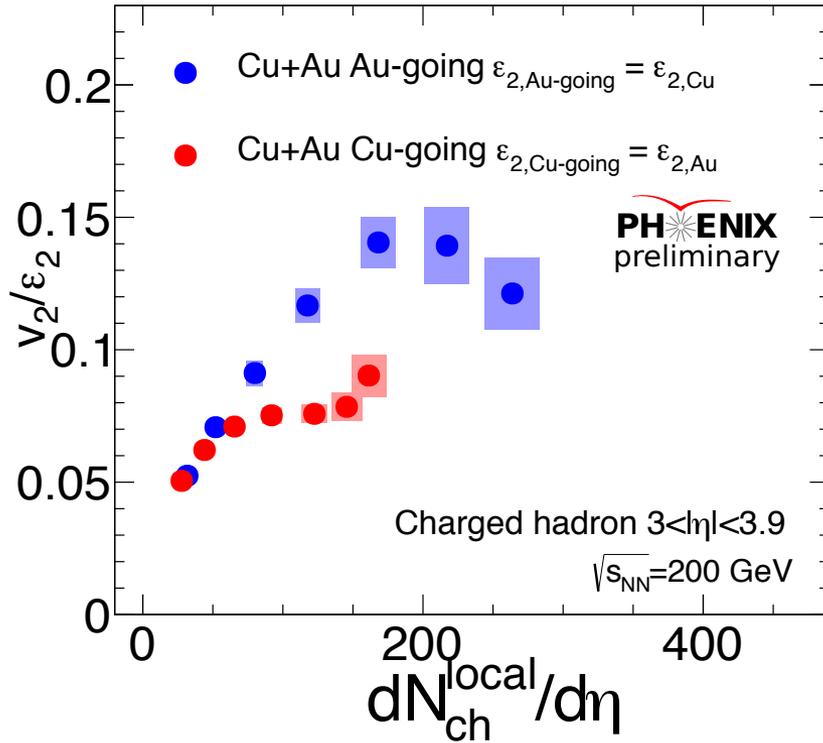
$v_n (dN/d\eta)$ at Au-going $\neq v_n (dN/d\eta)$ at Cu-going

$$v_n / \epsilon_n (1)$$



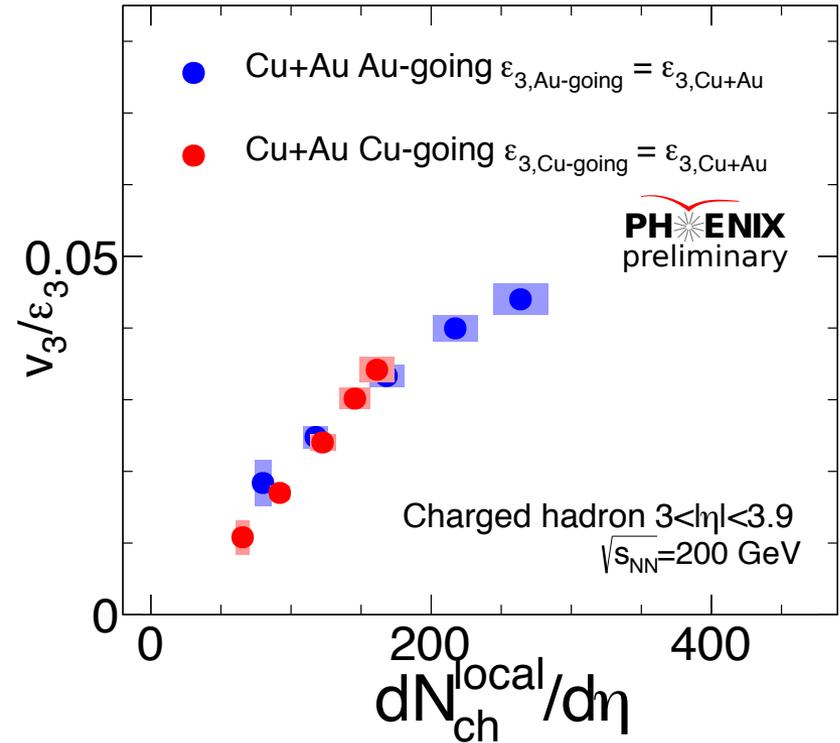
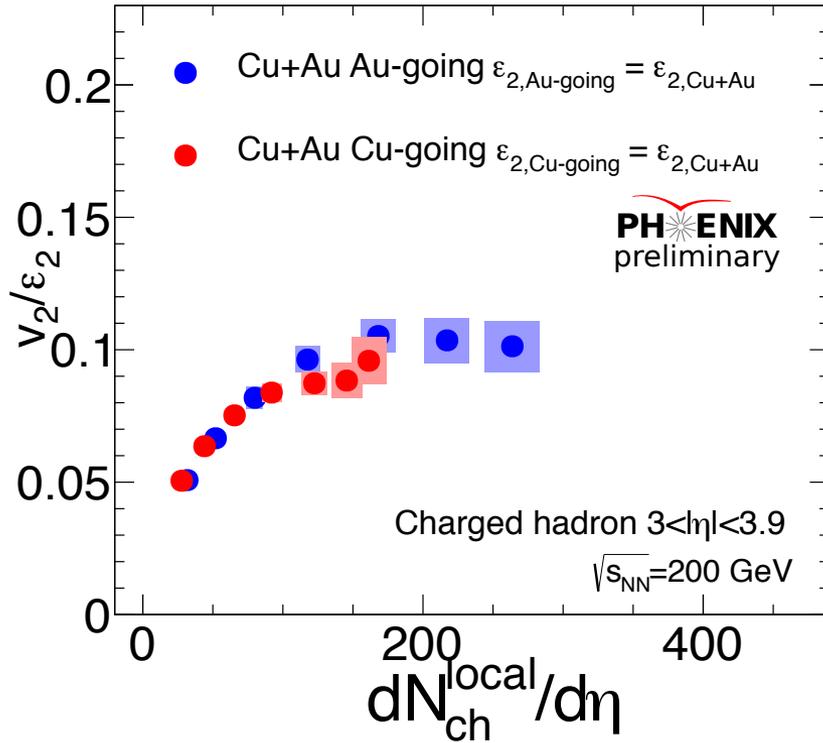
$(v_{n,Au\text{-going}} / \epsilon_{n,Au})$ and $(v_{n,Cu\text{-going}} / \epsilon_{n,Cu})$ do not agree.

$$v_n / \varepsilon_n (2)$$



$(v_{n,Au-going} / \varepsilon_{n,Cu})$ and $(v_{n,Cu-going} / \varepsilon_{n,Au})$ do not agree.

$$v_n / \varepsilon_n (3)$$

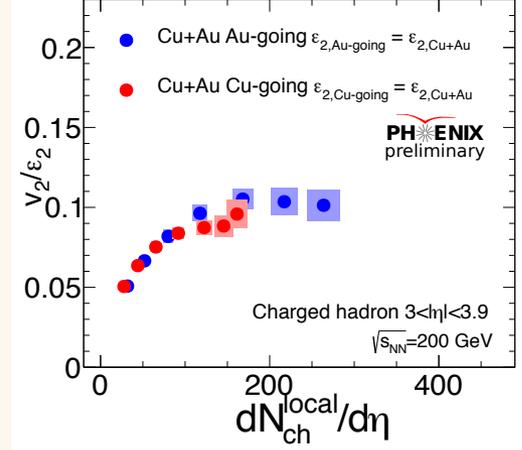
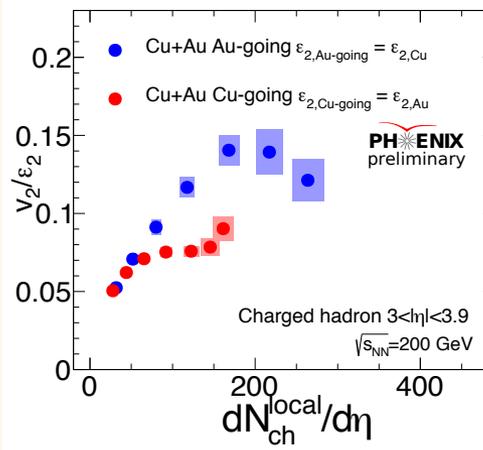
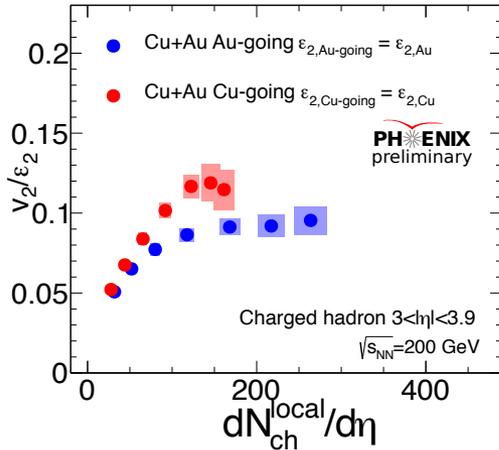
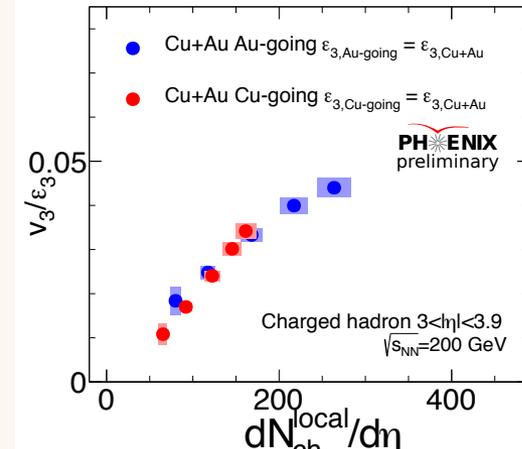
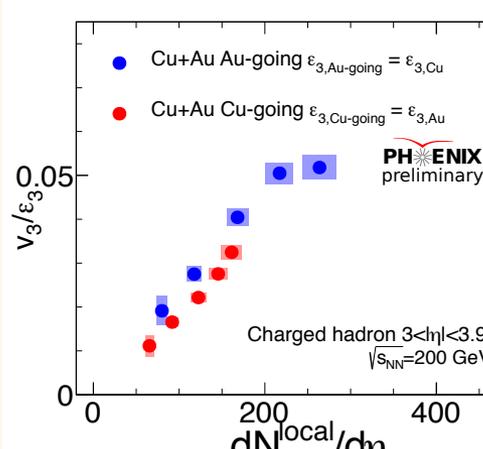
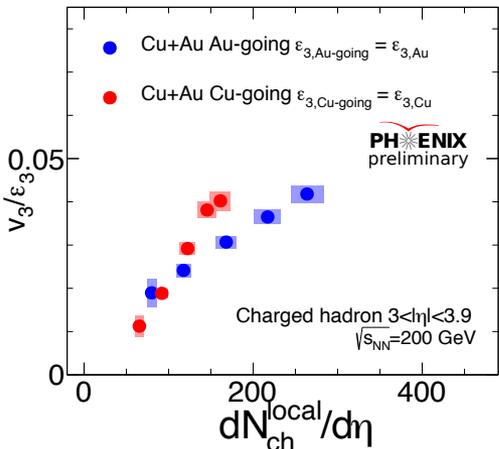


($v_{n,Au-going} / \varepsilon_{n,CuAu}$) and ($v_{n,Cu-going} / \varepsilon_{n,CuAu}$) agree!

$$(1) \frac{V_{n,Au-going}}{V_{n,Cu-going}} \Big/ \frac{\varepsilon_{n,Au}}{\varepsilon_{n,Cu}}$$

$$(2) \frac{V_{n,Au-going}}{V_{n,Cu-going}} \Big/ \frac{\varepsilon_{n,Cu}}{\varepsilon_{n,Au}}$$

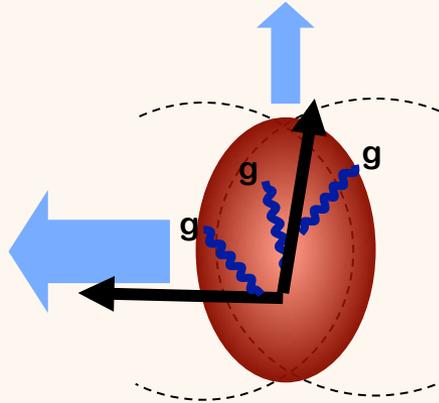
$$(3) \frac{V_{n,Au-going}}{V_{n,Cu-going}} \Big/ \frac{\varepsilon_{n,CuAu}}{\varepsilon_{n,CuAu}}$$

 V_2

 V_3


- F/B asymmetry is caused by $dN/d\eta$ (initial energy density).

v_2 for charged hadrons at high p_T

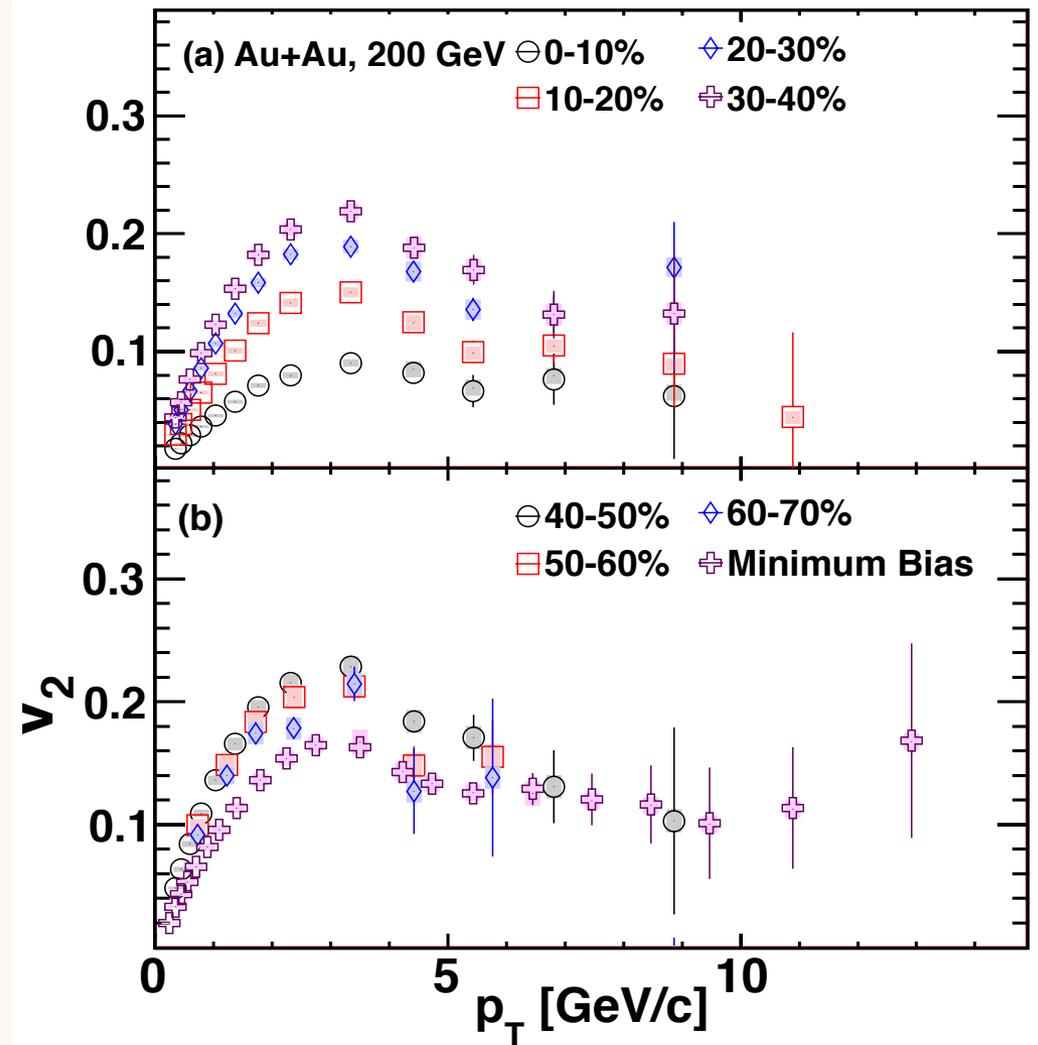
Azimuthal anisotropy at high p_T



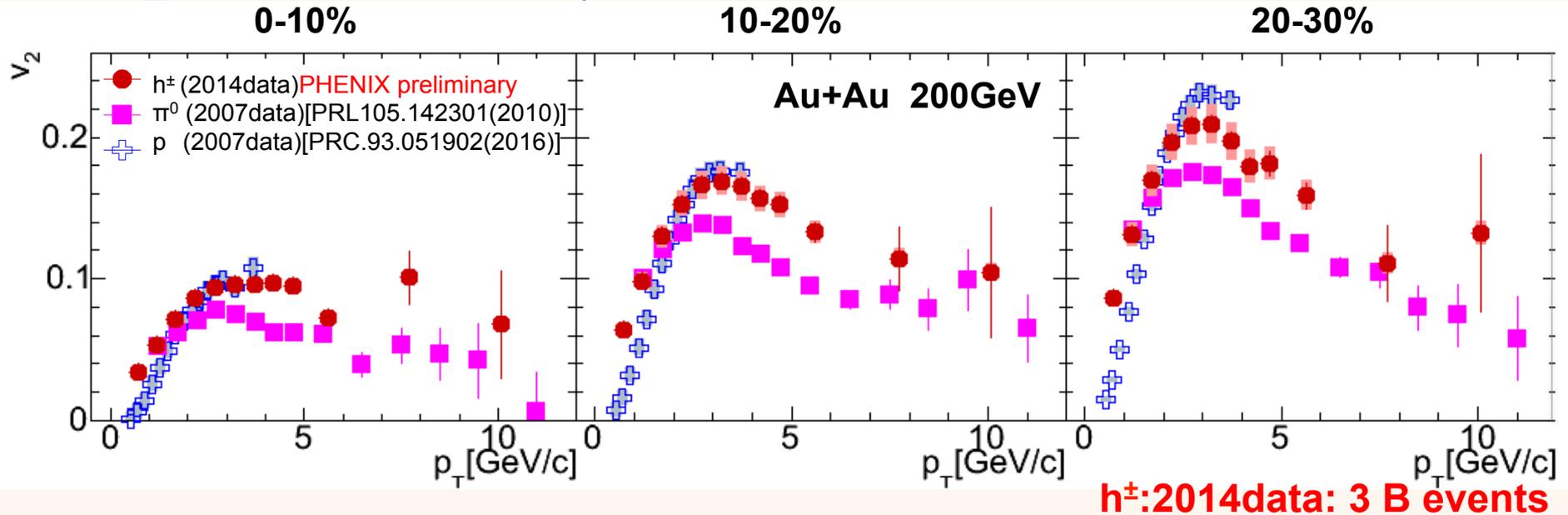
[PHENIX: PRC.92.034913 (2015)]

2004 data: 800 M events

- v_2 measurement is same as low p_T , but reasons are different.
- v_2 at high p_T is due to initial anisotropy and parton energy loss.

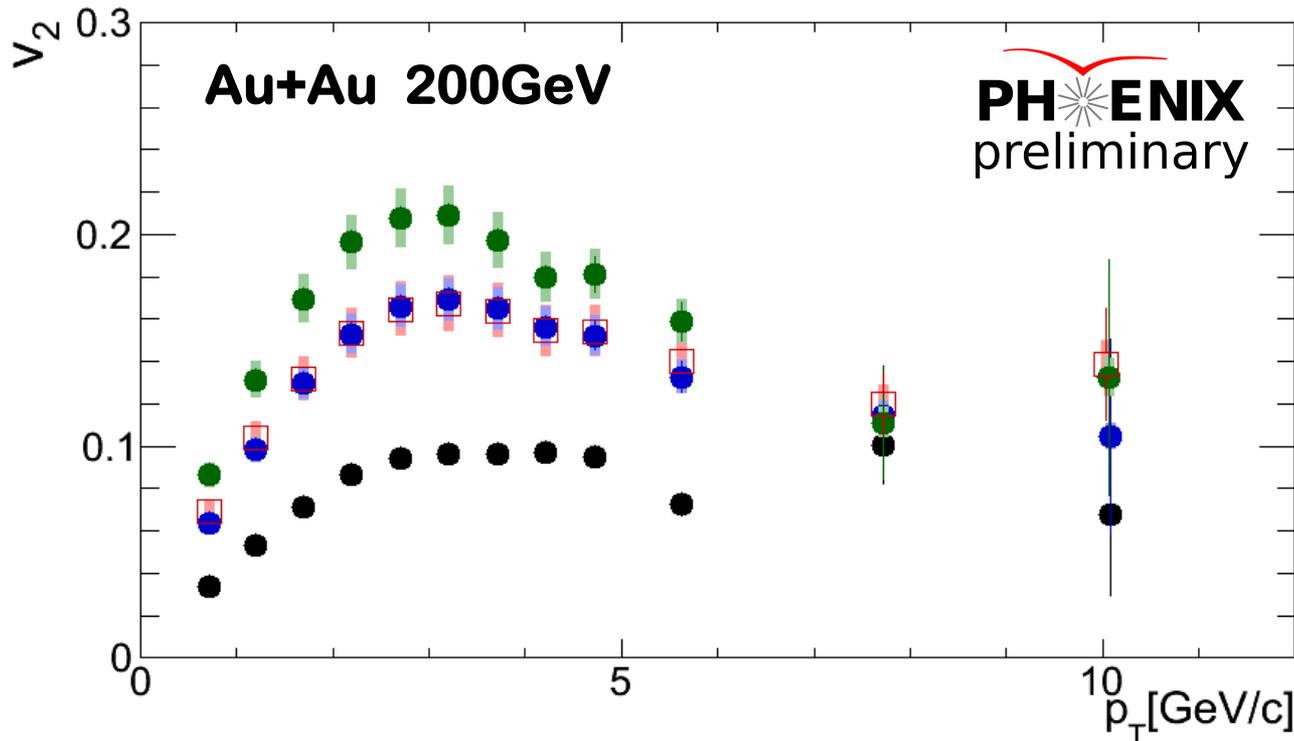


v_2 at high p_T in Au+Au at 200GeV



- Difference between charged hadron and π^0 v_2 diminishes with p_T .
- Proton contribution is seen at more central collisions.

High p_T v_2 at different centralities

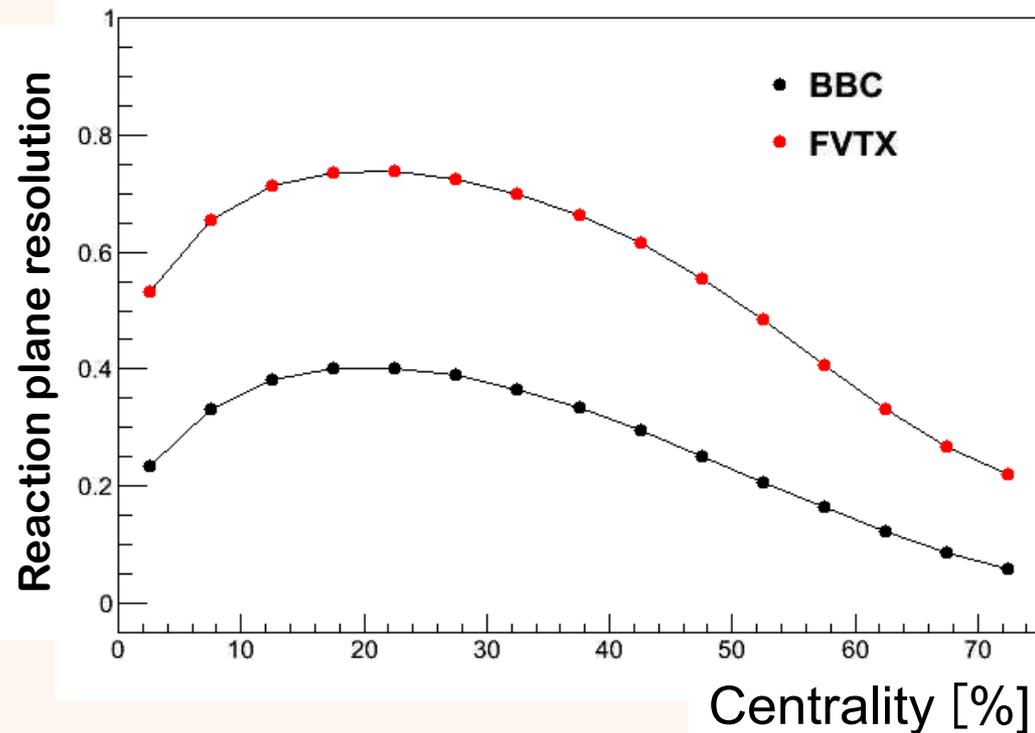


- At $p_T > 6\text{GeV}/c$, v_2 s of different centralities converge.
- This is not consistent with path-length dependent energy loss, large uncertainties notwithstanding.

Upcoming improvement to high $p_T v_2$

Improvements are expected with:

- 8 times larger statistics with all 2014+2016 data. (3B \rightarrow 12+12 B)
- 2 times better RP resolution with FVTX
- Tuning EMCAL energy cut depending on p_T to increase signal tracks at high p_T .



Summary

➤ Energy scan

✓ v_n is saturated from $\sqrt{s_{NN}}=39$ GeV up to 5 TeV.

➤ Forward/Backward v_n in Cu+Au

✓ $dN/d\eta(\text{Au-going}) > dN/d\eta(\text{Cu-going})$

✓ $v_n(\text{Au-going}) > v_n(\text{Cu-going})$

✓ Initial geometry could be boost invariant at same $dN/d\eta$ between $-4 < \eta < +4$

➤ v_2 for charged hadrons at high p_T

✓ At higher p_T , no significant difference in v_2 between charged hadrons and π^0 .

✓ At p_T above 6 GeV/c, v_2 looks constant around 0.1 from centralities around 0-30% within uncertainties that will be reduced in the future.

Related PHENIX Posters

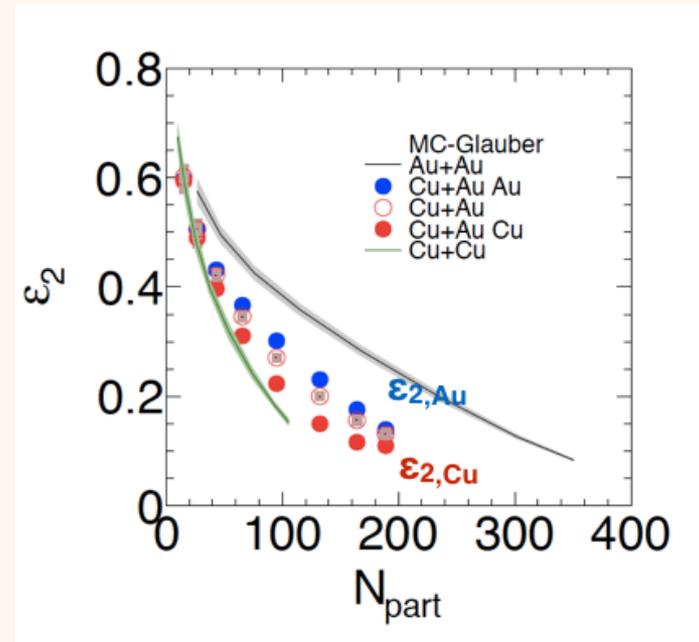
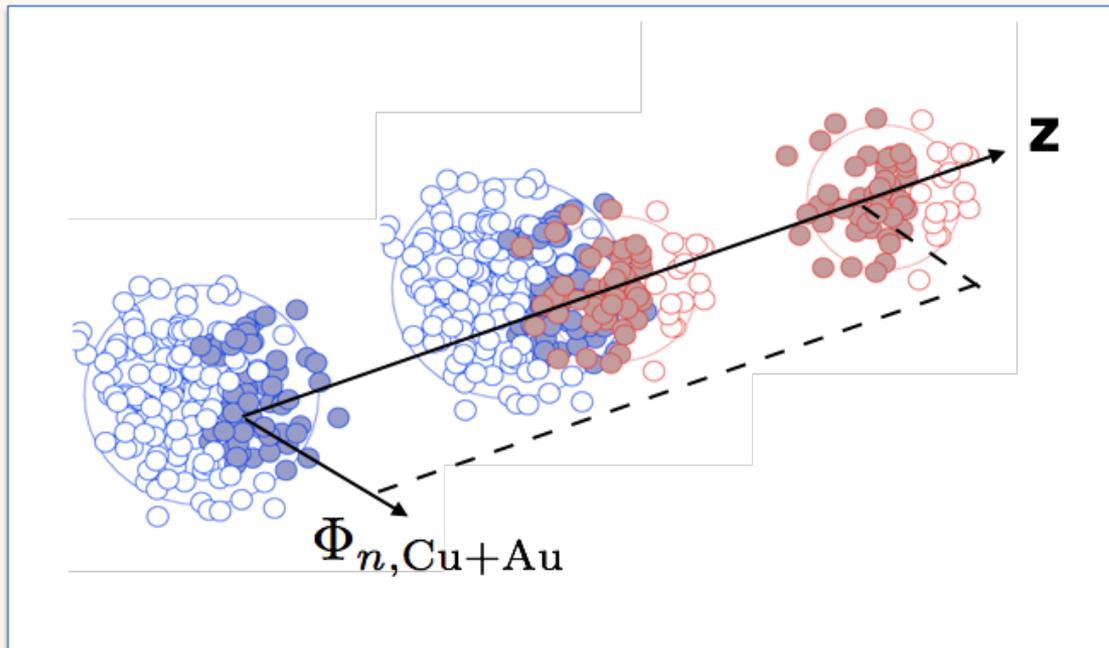
[Poster]

- *K03:NAKAGOMI Hiroshi*

Forward/Backward asymmetry of v_n in
Cu+Au at RHIC-PHENIX

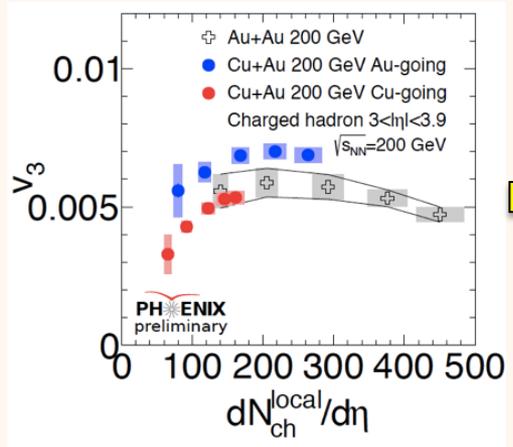
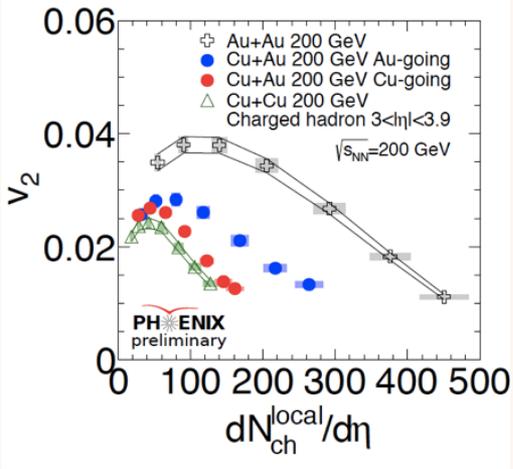
Back Up

$$\varepsilon_{n,Au}(Cu) = \frac{\langle r^n \cos[n(\phi_{Au}(Cu) - \Phi_{n,Cu+Au})] \rangle}{\langle r^n \rangle}$$



$v_{n,Au-going}$

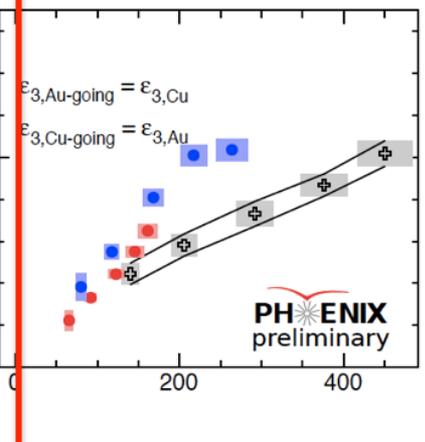
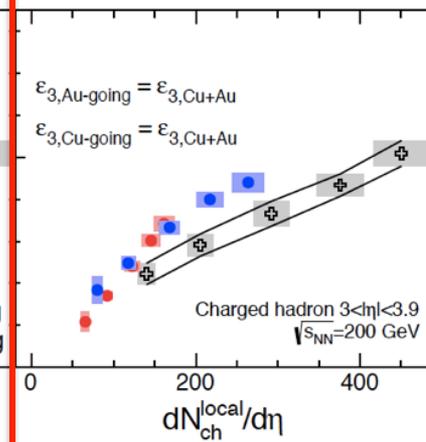
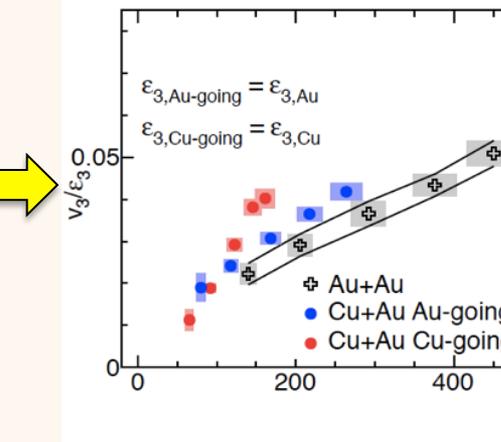
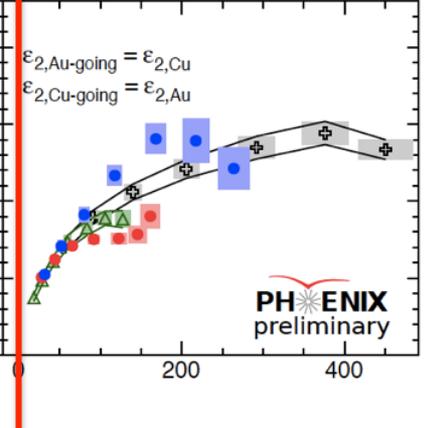
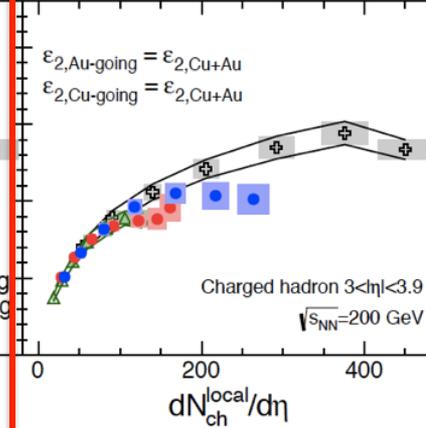
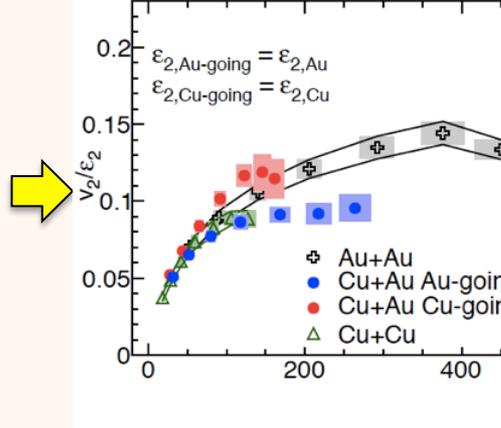
$v_{n,Cu-going}$



$v_{n,Au-going} / \epsilon_{n,Au}$
 $v_{n,Cu-going} / \epsilon_{n,Cu}$

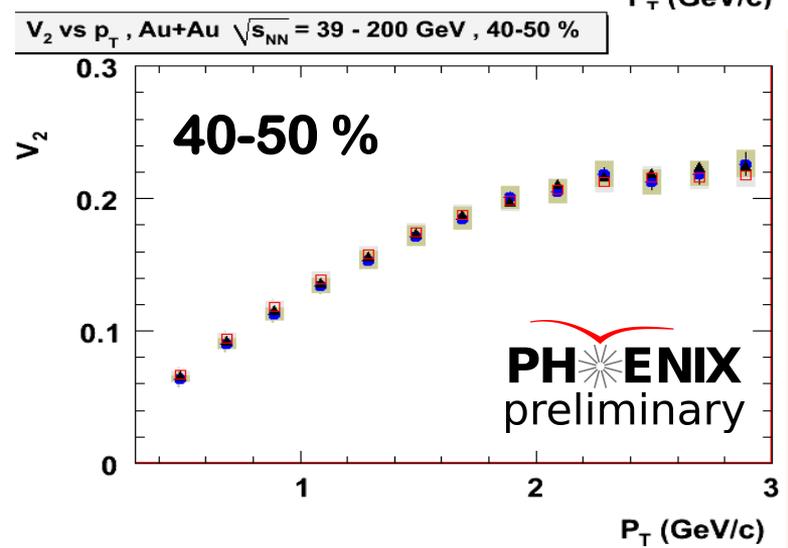
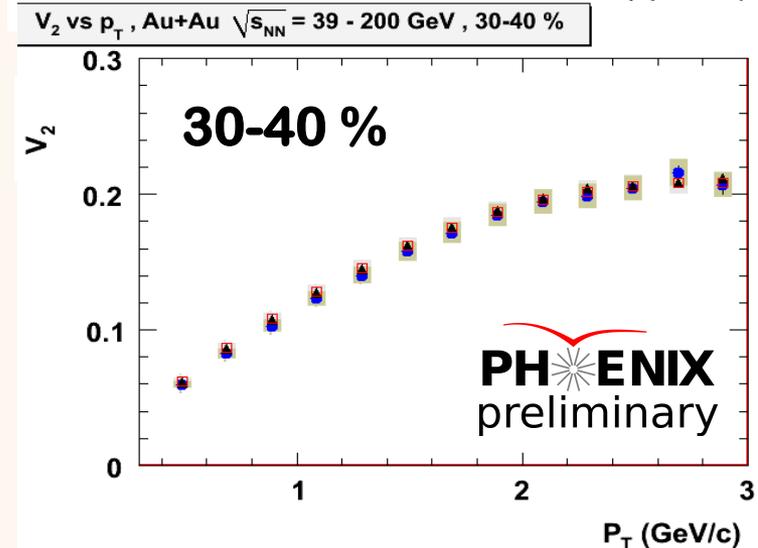
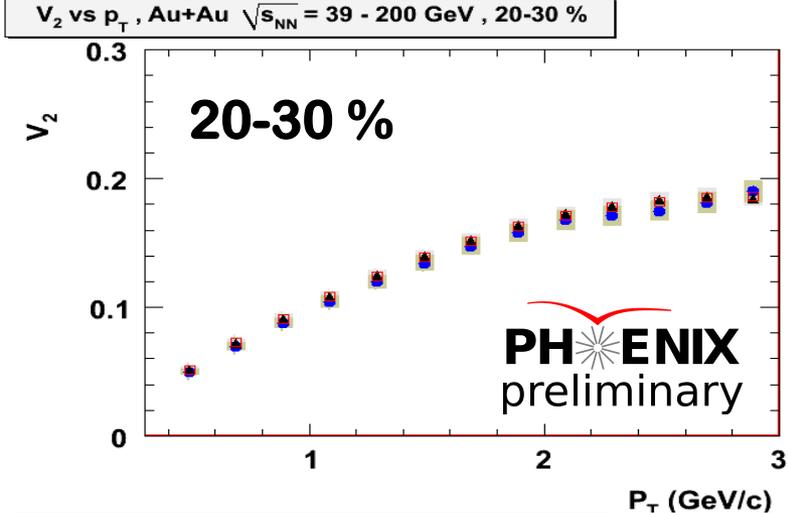
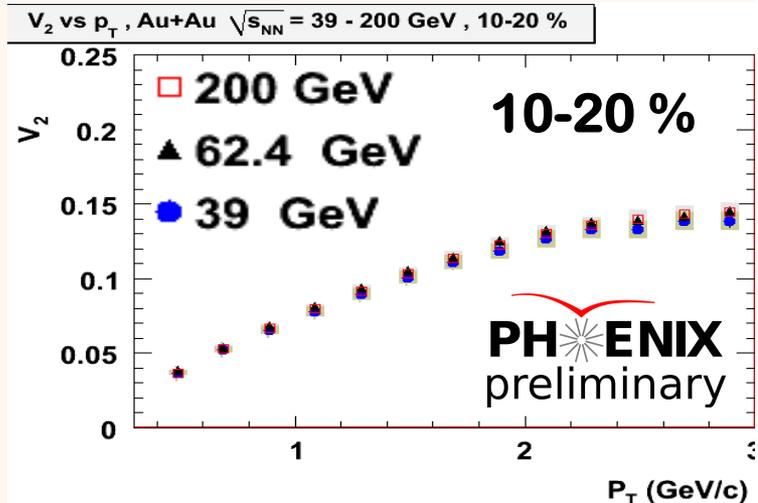
$v_{n,Au-going} / \epsilon_{n,CuAu}$
 $v_{n,Cu-going} / \epsilon_{n,CuAu}$

$v_{n,Au-going} / \epsilon_{n,Cu}$
 $v_{n,Cu-going} / \epsilon_{n,Au}$



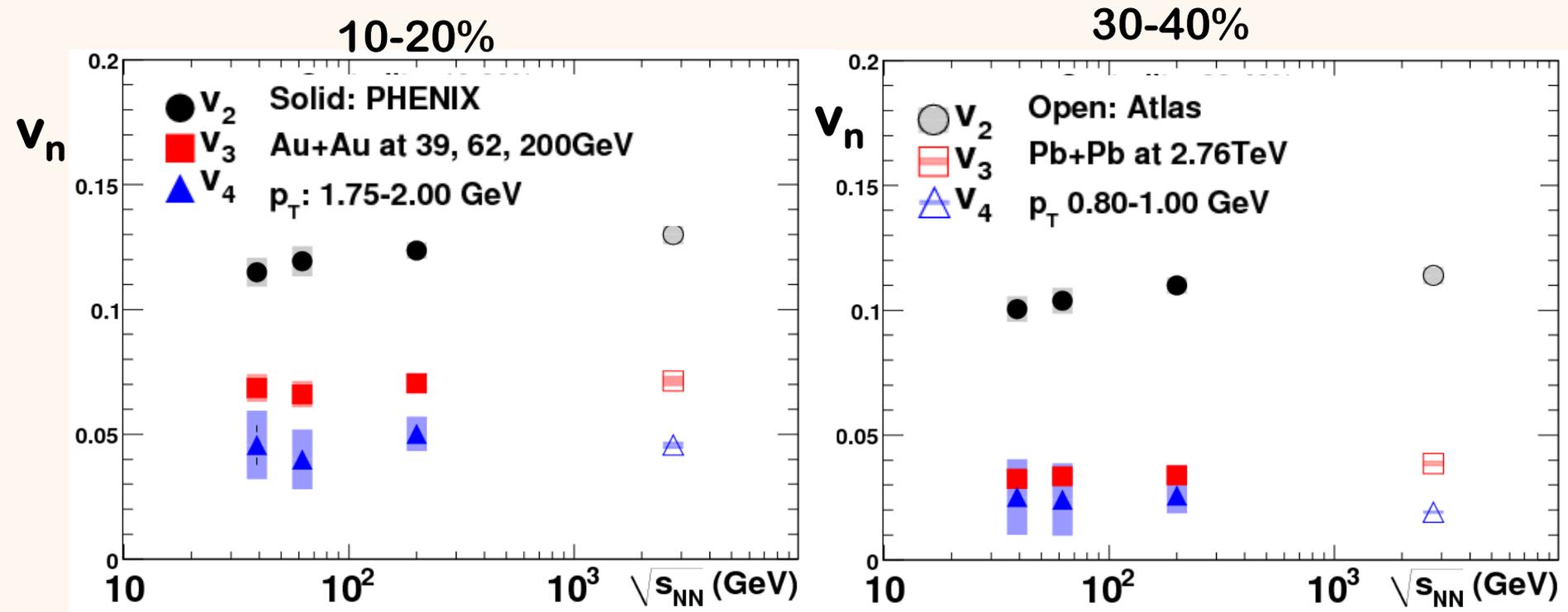
- Common $\epsilon_{n,Cu+Au}$ scales v_n at both Au-going and Cu-going.
- F/B asymmetry is caused by $dN/d\eta$ (initial energy density).

v_2 at 200, 62.4 and 39 GeV

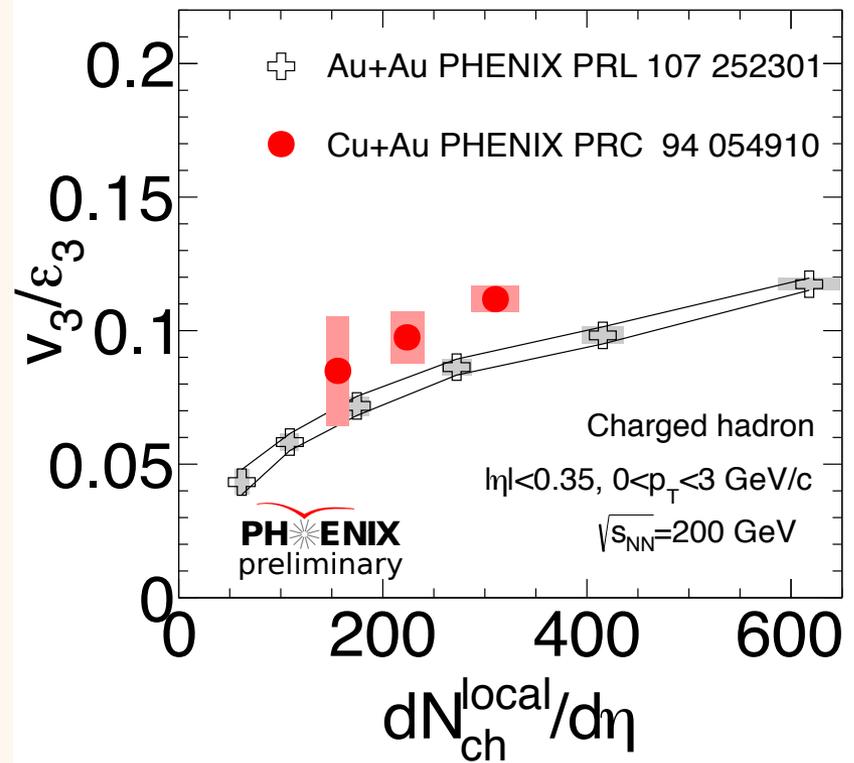
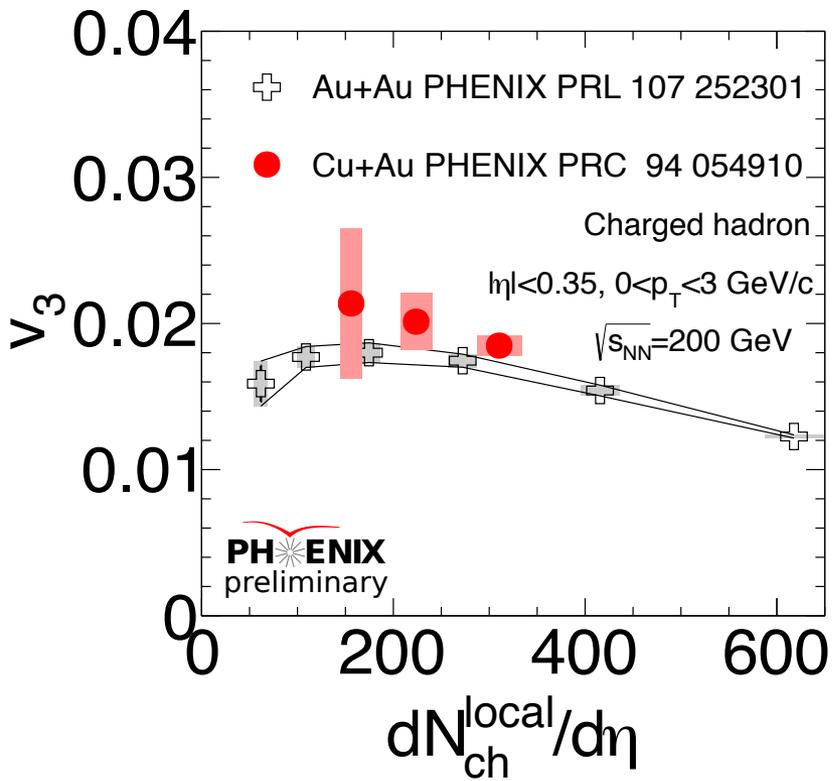


$v_2(p_T)$ is already saturated at 39 GeV !

v_n saturation up to LHC energy

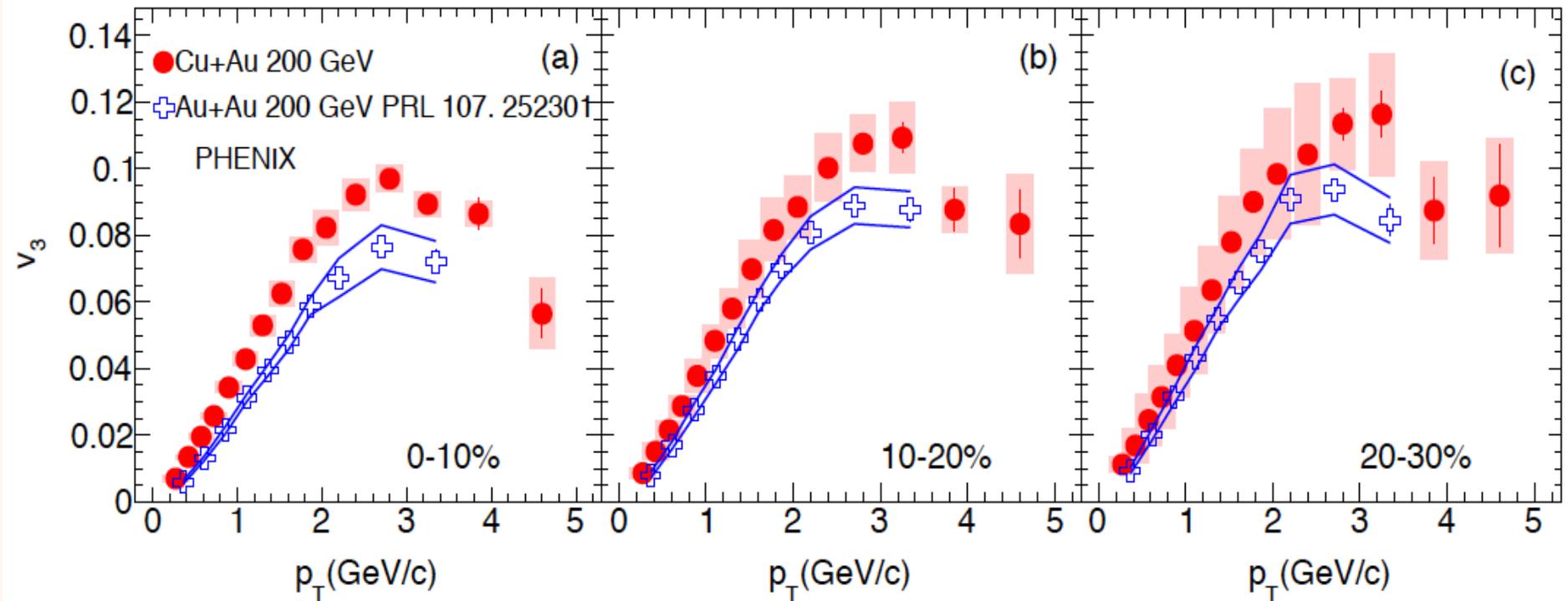


v_2 , v_3 and v_4 are saturated from 39 GeV up to LHC energy.

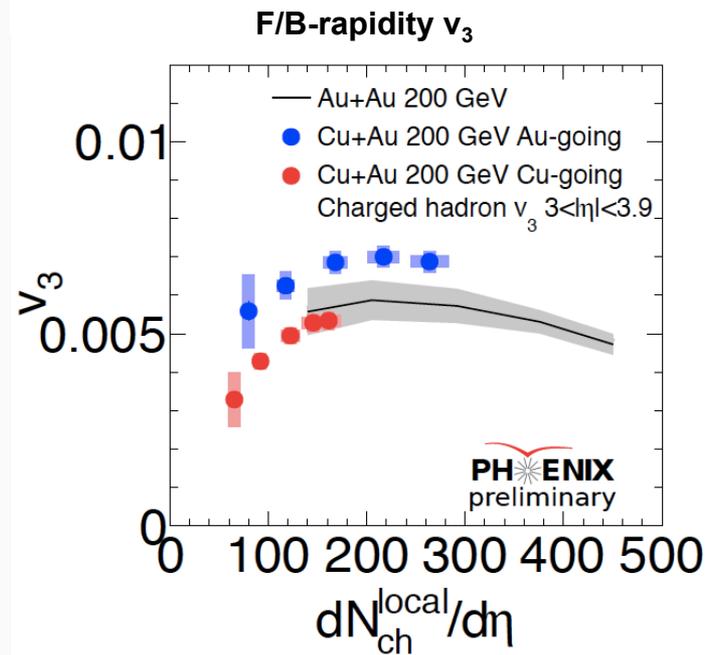
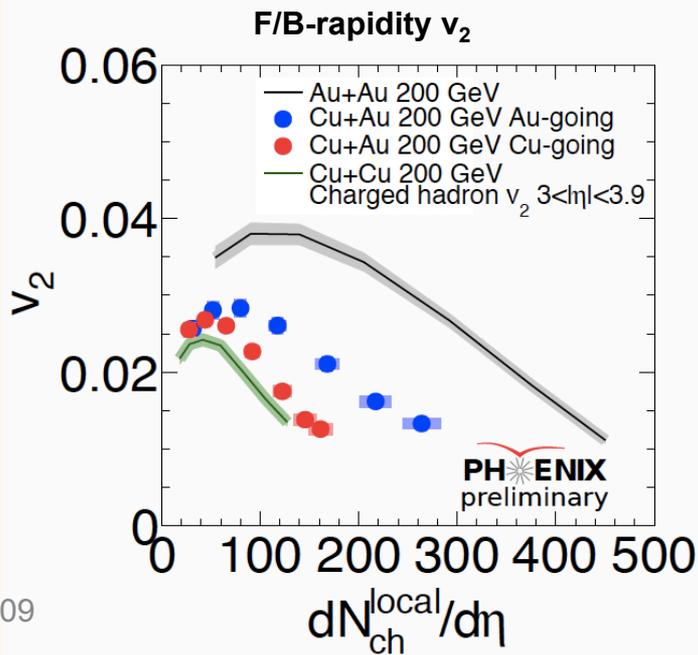
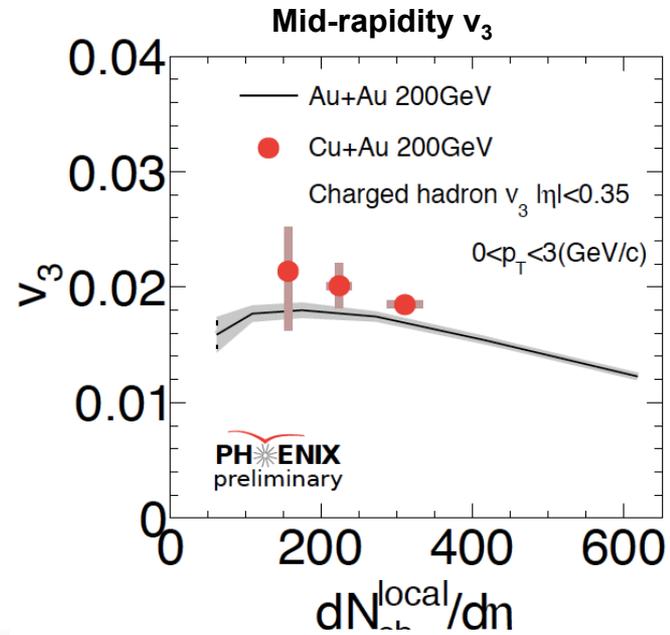
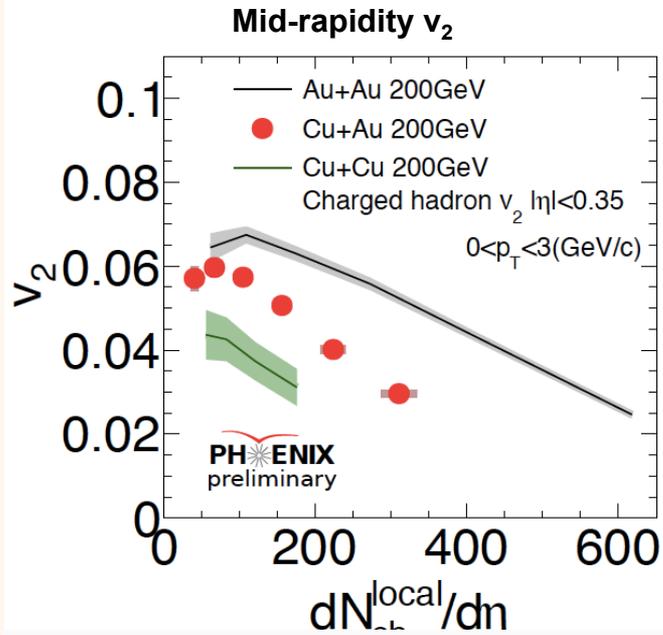


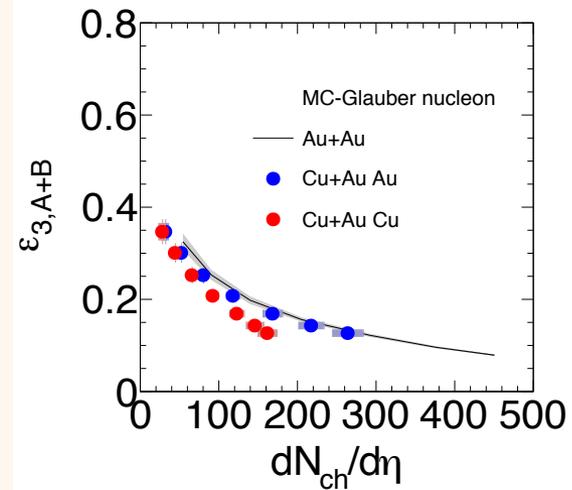
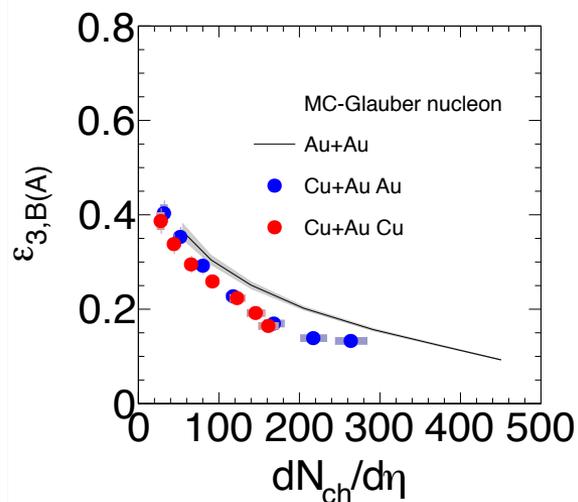
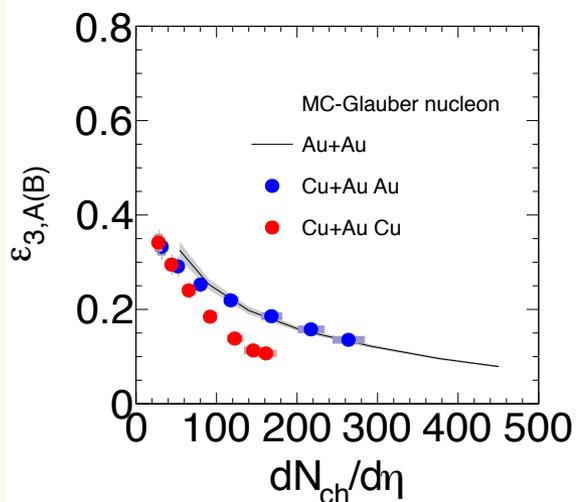
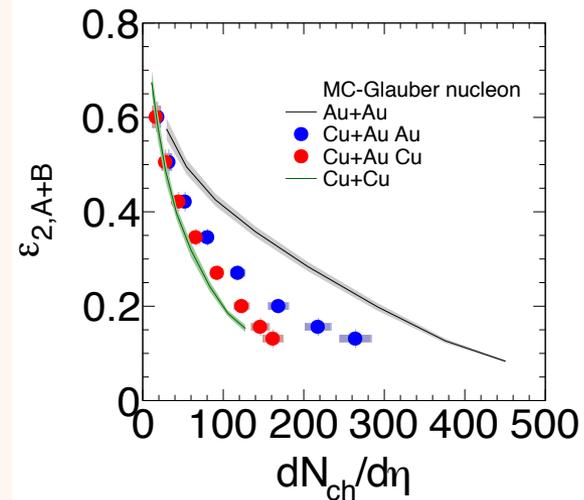
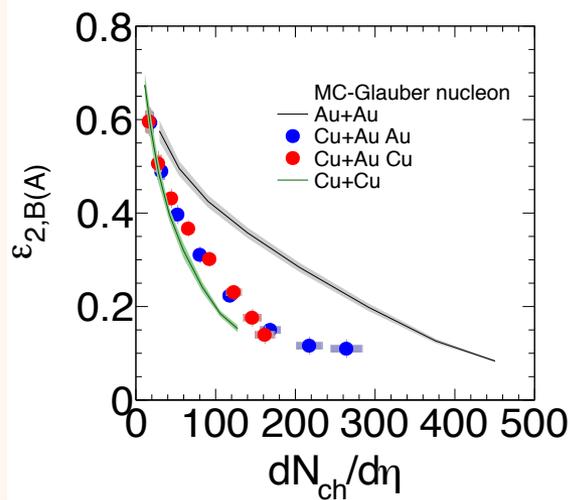
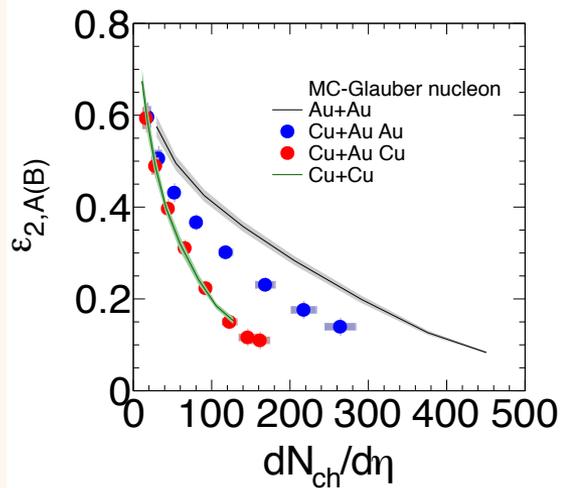
v_3 vs. p_T for AuAu/CuAu

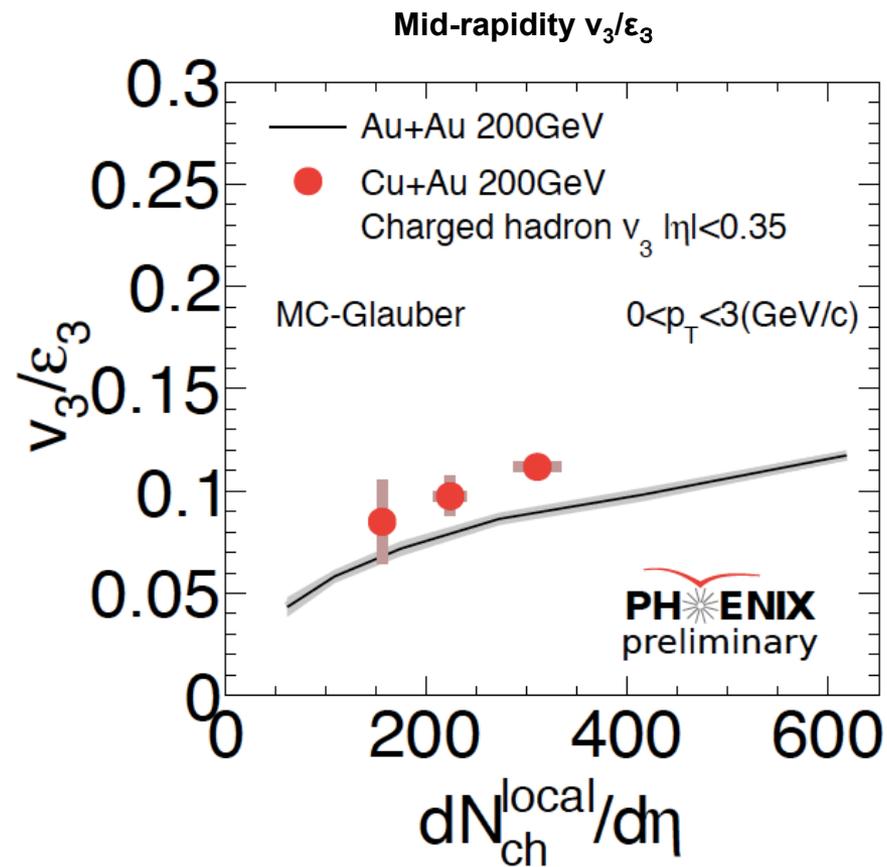
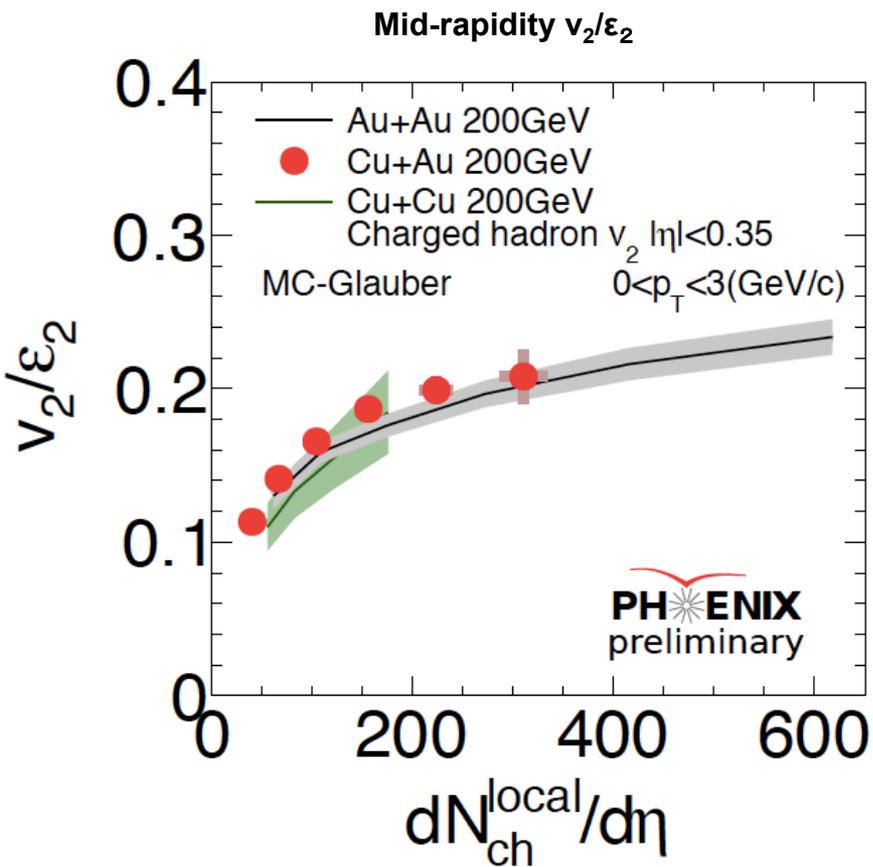
arxiv:1509.07784



- Weak centrality dependence in AuCu
- CuAu is always bigger than AuAu.

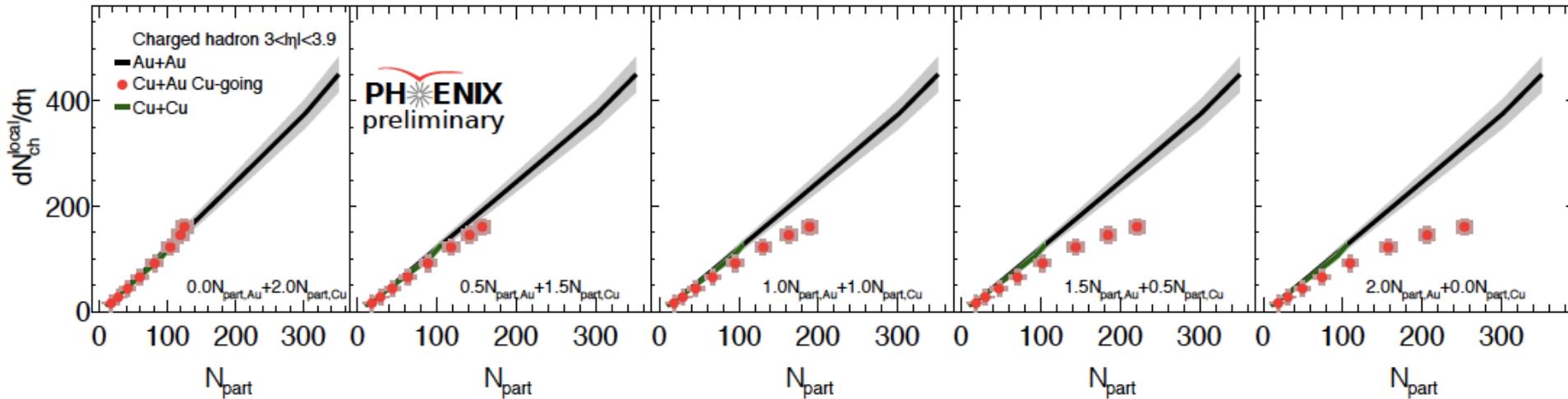




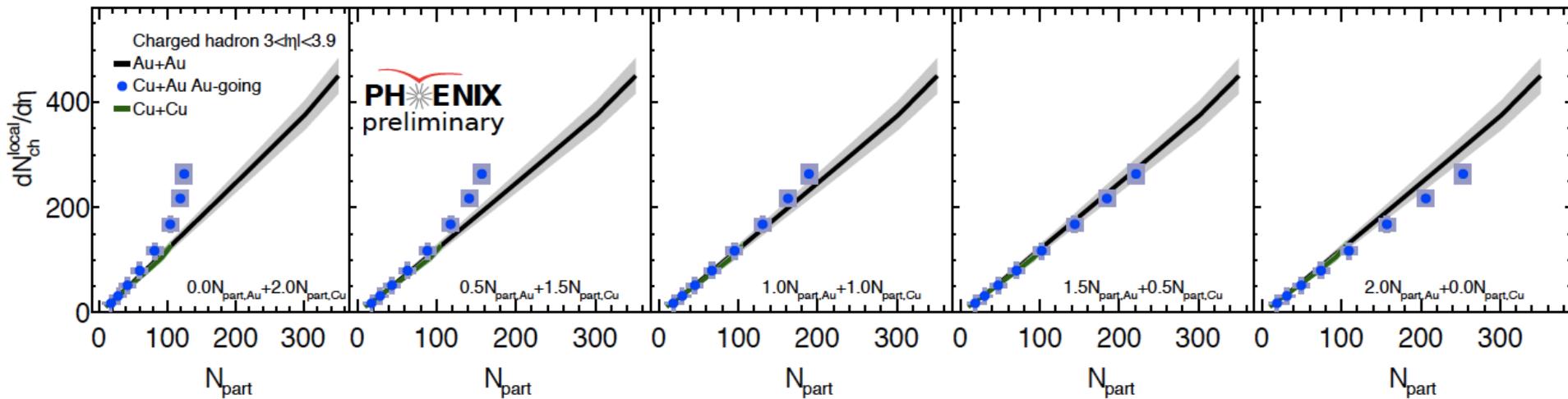


Weighted N_{part} scaling : $N_{\text{part}} = w \cdot N_{\text{part,Au}} + (2-w) \cdot N_{\text{part,Cu}}$ ($2 \cdot N_{\text{part,Cu}} < N_{\text{part}} < 2 \cdot N_{\text{part,Au}}$)

Cu-going side $dN/d\eta$



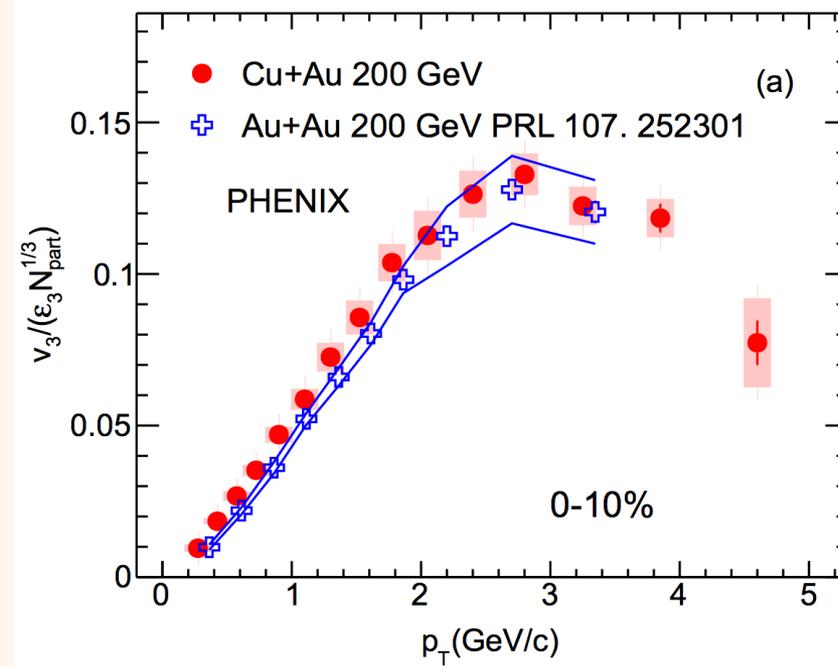
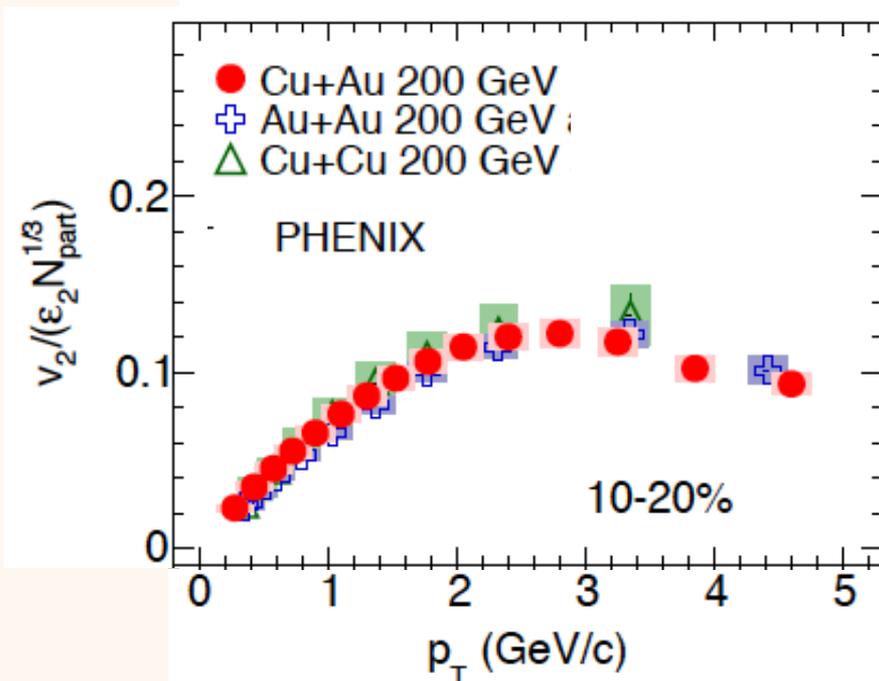
Au-going side $dN/d\eta$



$v_n/(\epsilon_n * N_{part}^{1/3})$ in Cu+Au (mid-rapidity)

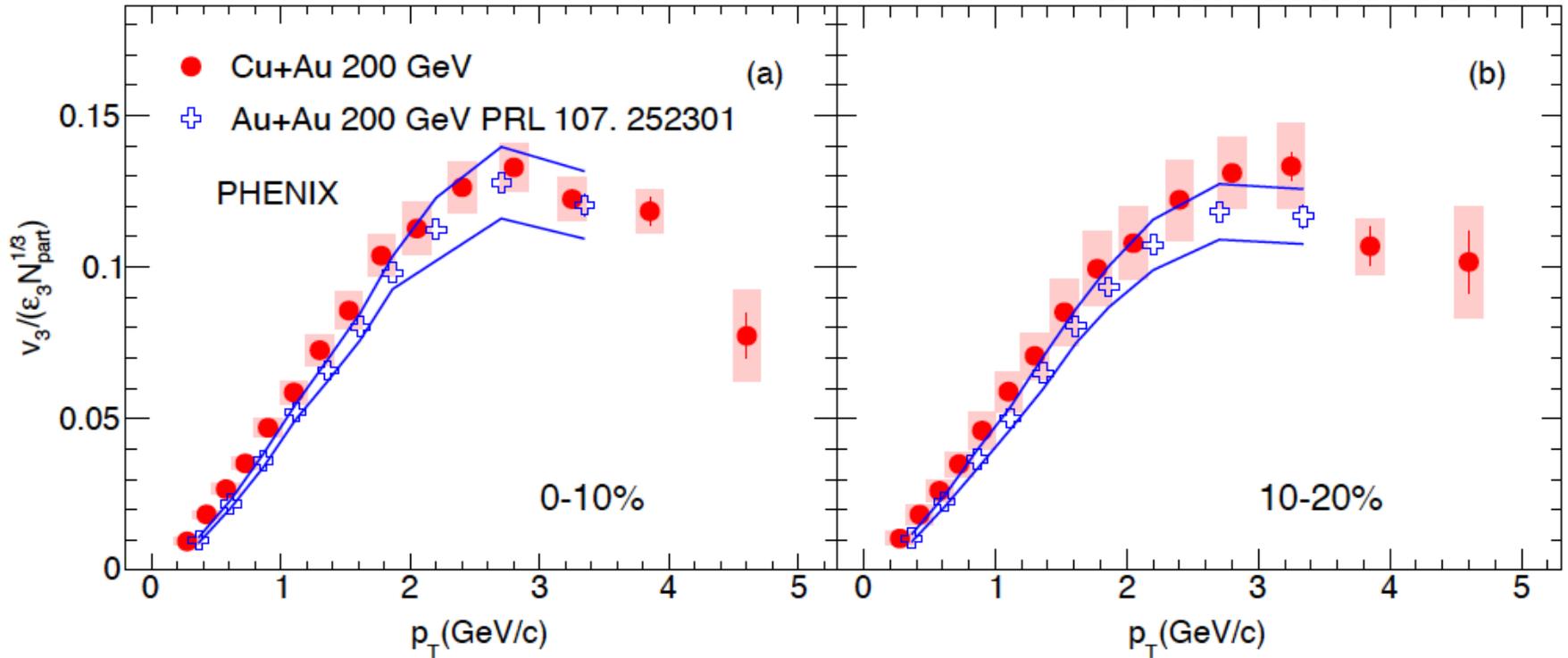
[PRC.92.034913]

[PRC94,054910]



$\epsilon_3 * N_{\text{part}}^{(1/3)}$ scaling for v_3

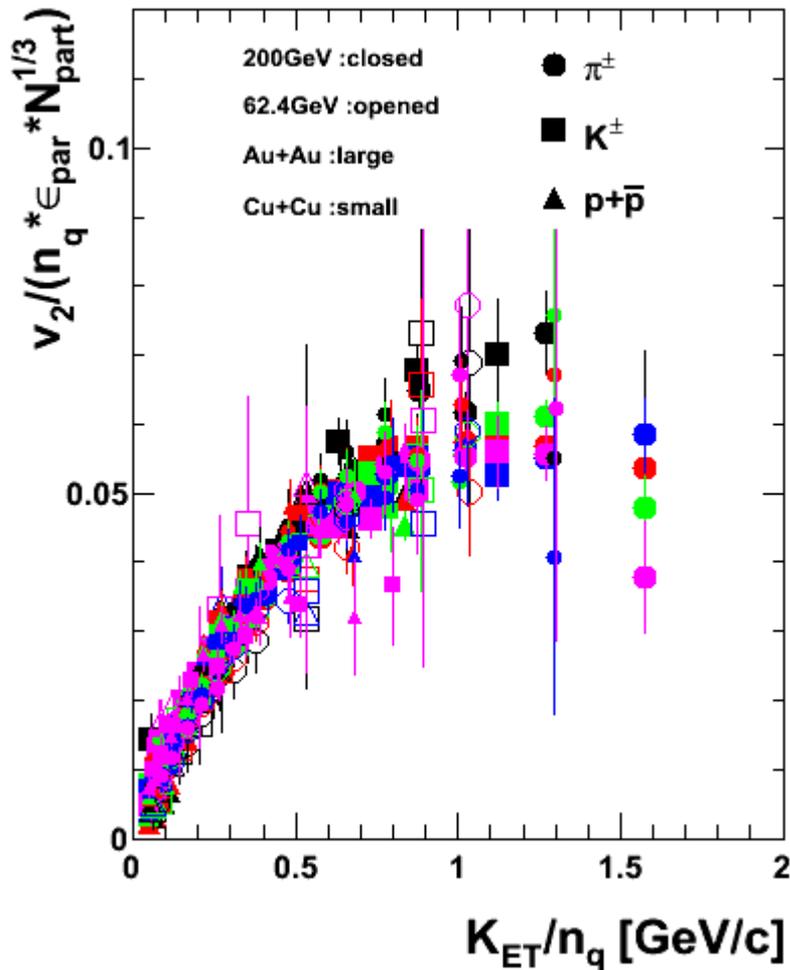
arxiv:1509.07784



$\epsilon_3 N_{\text{part}}^{(1/3)}$ scaling works well in v_3 .

Scaling

$v_2(K_{ET}/n_q)/n_q/\epsilon_{par}/N_{part}^{1/3}$



- ◆ Different Energy and System (AuAu200, CuCu200, AuAu62)
- ◆ Different Centrality (0-50%)
- ◆ Different particles (π / K /p)

$$\frac{v_2(K_{ET} / n_q)}{n_q \times \epsilon \times N_{part}^{1/3}}$$

Almost scale to one curve.